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# Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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# Journal of Sedimentary Petrology

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

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Diagnostic heavy minerals in the regolith of Massachusetts. By M. A. Light.

Clay minerals of the Neuse River Estuary. By G. M. Griffin and R. L. Ingram.

The nature of corrosion zones in the Middle Ordovician of Minnesota. By N. Prokopovich.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 2, PP. 83–110
FIGS. 1–14, JUNE, 1955

# ORIGIN OF THE SALINA SALT OF MICHIGAN[1]

LOUIS F. DELLWIG
University of Kansas, Lawrence, Kansas

## ABSTRACT

The purpose of this study was to determine the manner of deposition of the Salina salt, including the approximate temperature of deposition and the origin of the dolomite-anhydrite laminae.

Specimens were obtained from drill cores from the Michigan basin and from the Detroit mine of the International Salt Company. The bulk of the data was obtained through thin section study and this was supplemented by the examination of polished slabs, water-insoluble residues, and sections of core from which the salt had been dissolved.

Pyramidal shaped hopper crystals of halite, comparable to those crystals produced in the manufacture of grainer salt and those formed in the manufacture of solar salt, were identified in the Salina salt. The pyramidal forms were outlined by liquid inclusions, and from these inclusions the temperatures of formation were determined as being between 32.0 and 48.4° C.

The salt was deposited in layers or bands of three distinct types: (1) cloudy layers of inclusion-rich pyramidal shaped hopper crystals of halite, (2) clear layers of inclusion-free halite, and (3) laminae of anhydrite and dolomite. These units are in part obscured in the recrystallized salt.

The alternation of bands of clear and cloudy halite was the result of temperature changes probably related to the seasons. The salt crystals, initially formed on the surface, grew as pyramidal shaped hoppers. Until the brine became saturated, settling hopper crystals were dissolved. After the saturation point had been reached pyramidal shaped hopper crystals accumulated on the bottom of the basin to form a layer of cloudy salt. With subsequent cooling the brine passed into the supersaturated state and settling hopper crystals provided nuclei for clear overgrowths. These crystals which grew on the bottom of the basin are inclusion-free and form the layers of clear salt. The return of higher temperatures followed again by lower temperatures would cause a repetition of this sequence. This cycle could have been interrupted at any time by the addition of brine to the basin or by periods of unusual climatic conditions.

The deposition of the anhydrite-dolomite laminae may be considered to have been the result of the influx of normal sea water. The addition of brine to the basin as a surface layer would have permitted the maintenance of life in this brine until the concentration reached the point at which mass extermination took place. Subsequent decomposition of the remains caused reducing conditions to develop in the basin and iron precipitated as pyrite. Indicative of this influx is the association with the laminae of carbonaceous material, pyrite, and a petroliferous odor and the lack of a recognizable relationship between the clear or cloudy salt and the anhydrite-dolomite laminae. Iron associated with the halite layers is in the form of hematite, indicating that oxidizing conditions were normal for the basin.

## INTRODUCTION

The Salina formation includes the earliest evaporites deposited in the Michigan basin. The Salina formation and the overlying Bass Island dolomite comprise the Cayugan group of the Silurian system. In the Michigan basin the Salina formation has been divided into seven distinct units (Landes, 1945). Three units are of shaly dolomite or dolomitic shale, three are predominantly of salt, and the seventh is a basal dolomite which contains increasing amounts of salt toward the center of the basin.

This study initially centered itself around drill cores filed in the core library of the University of Michigan. A comprehensive examination of cores which cut through the Salina formation showed that the thick salt beds could generally be divided into two contrasting units. The one unit (fig. 1) is even bedded salt with layers of salt three to eight centimeters thick alternating with tissue thin laminae of anhydrite and dolomite. The halite crystals average less than one centimeter in diameter. Generally there

[1] Condensation of Ph.D. Thesis at University of Michigan.

FIG. 1.—A section of core from the Glen Bradley No. 4 well, Newaygo, Co., Michigan; 273 feet above the base of the Salina formation. Core depth—4882 feet. The black areas are predominately anhydrite; the dark grey areas are anhydrite intermixed with halite. Both the clear and the cloudy areas are halite. ×0.7

is a crude layering of clear and cloudy salt. Megascopically the laminae are continuous and flat. In the other unit (fig. 2) the bedding is extremely irregular. The individual halite crystals average several centimeters in diameter, some attaining a diameter in excess of five centimeters. Almost all of the crystals are clear. The laminae are distorted and irregular. Mineralogically, the units show almost no variation. In addition to dolomite and anhydrite, there are contained within the laminae quartz, pyrite, celestite, polyhalite, and carbonaceous material. Complex salts are rare, precipitation apparently being terminated before the development of the polyhalite phase in the theoretical sequence of deposition of salts (table 1).

The first unit (even bedded salt) is now essentially as it was originally deposited; the second unit (irregularly bedded salt) has undergone extensive recrystallization. The disruption or distortion of the laminae indicates that the recrystallization is not a process associated with the original deposition of the halite and the anhydrite and dolomite laminae, and is not involved in the development of a theory of deposition for the Salina salt.

Some phases of Salina salt deposition have previously been described. Near shore conditions of deposition have been studied by Kaufmann and Slawson (1950) and a second paper on deposition in the marginal areas is in preparation by the same authors. The economic importance of the Salina salt has been responsible for several additional studies of a more general nature (Cook, 1914; Grabau and Sherzer, 1910; Sherzer, 1911). The Salina salt of Michigan is also considered in the more general discussions of evaporites by Grabau (1913, 1920), Phalen (1919), and Lotze (1938).

## Acknowledgments

The author is most desirous of expressing his thanks to those who helped make this work possible. Dr. L. I. Briggs has offered many hours of consultation and assistance, especially in the development of the physical-chemical aspects of deposition. Professors Landes and Slawson provided specimens for comparative study and freely shared their unpublished findings concerning salt deposition. The carbonaceous material was examined by Professor Chester A. Arnold. Mr. J. C. Buchen of the Leslie Salt Company furnished helpful data regarding the deposition of solar salt. Through the co-

FIG. 2.—A section of core from the Glen Bradley No. 4 well, 17 feet above the base of the Salina formation. Core depth—5138 feet. In this section recrystallization of the salt has caused the enlargement of the halite crystals, the elimination of the banding of clear and cloudy halite, and the deformation of the anhydrite laminae. The apparent thickness of the laminae is due to their wavy character. The black areas are predominately anhydrite; the dark grey areas are anhydrite intermixed with halite. Both the clear and cloudy areas are halite. ×0.7.

operation of Mr. L. E. Read and his staff at the Detroit mine of the International Salt Company, the mine workings were studied and much valuable information was obtained. Special thanks are due to Mr. D. E. Kaufmann of the International Salt Company. His information on manufacturing processes contributed much to the development of certain theoretical aspects of the problem. He also provided numerous samples for study.

## Method of Study

The greater part of the data was collected from the core of the Glen Bradley No. 4 well in Newaygo County, Michigan. The samples were taken from "Unit A" (lowermost salt) as classified by Landes (1945). The well is located in the NE¼ SW¼ SE¼ Sec. 11, T. 12 N., R. 13 W. At this point the Salina formation is approximately 1400 feet thick. The base of the Salina formation was intersected at about 5155 feet. The core is about 3.5 inches in diameter. Although the core is not from the center of the basin, the salt represents conditions of deeper water deposition than does the material from the Detroit mine. Additional cores were studied for substantiating or conflicting evidence.

Examination of the workings of the Detroit mine of the International Salt Company yielded much information which was not available from the core study. The mine shaft is located in Oakwood in the NW¼ Sec. 33, T. 2 S., R. 11 E. Mining is being carried on at a depth of about 1140 feet, approximately 666 feet above the base of the Salina formation in "Unit F" as defined by Landes (1945).

Thin sections were supplemented with polished plates and the latter were especially valuable in showing three dimen-

TABLE 1.—*Theoretical profile for the evaporation of sea water at 25°C (Phillips, 1947)*

| | | | |
|---|---|---|---|
| Kieserite, carnallite, bischofite | Anhydrite | Halite | Bischofite zone |
| Kieserite, carnallite | | | Carnallite zone |
| Kieserite, kainite | | | |
| Hexahydrite, kainite | | | Kainite zone |
| Epsomite, kainite | Polyhalite | | |
| Epsomite | | | Potash-free magnesium sulphate zone |
| Blodite | | | |
| Polyhalite | | | Polyhalite zone |
| Anhydrite | | | Anhydrite zone |
| Gypsum | | | Gypsum zone |
| Carbonates | | | Basal limestone and dolomite |

sional relationships. Water insoluble residues were used to study crystal form and to identify some minerals.

In the preparation of the illustrations all photographs and photomicrographs have been oriented with the top of the section or specimen toward the top of the page.

## Geologic History of the Michigan Basin and Its Relationship to Salina Deposition

The initial depression of the Michigan basin, probably related to the Keweenewan disturbance (Pirtle, 1932), resulted from the same northeasterly pressure which was responsible for the development of the Lake Superior geosyncline. The basin is approximately 450 miles in diameter and has a slight elongation in a northwest-southeast direction. The average dip of the beds toward the center is 30 to 35 feet per mile. The basin is bounded on the west by the Wisconsin and Kankakee arches and on the east by the Findlay arch. Downwarping of the basin was periodic, and there is a thickening of the sediments in the central portion. Minor structures have developed parallel to the long axis of the downwarp. Coarse clastics are relatively scarce.

The sediments in the basin range in age from Cambrian to Permian(?). Evaporites were deposited during three periods beginning with the Salina formation of Late Silurian age. The problems of deposition of the subsequent evaporites may or may not be related to those of the Salina salt, for, at least in part, the younger evaporites may have been formed through solution and reprecipitation of the Salina salt.

During the Silurian the greater part of North America remained low with the exception of Appalachia. Limestone, dolomite, and subordinate fine clastic sediments are characteristic of lower and middle Silurian formations in the Michigan basin. The first isolation of the basin was during Niagaran time. Salina deposition began with widespread carbonate muds and anhydrite, although in some places salt is found directly above the Niagaran rocks. Salt was deposited above the carbonate muds and anhydrite and this in turn was followed by dolomitic muds. Deposition of dolomite, anyhdrite, halite, and shale continued until the end of the Silurian period.

The base of the Salina in the center of the basin now lies at a depth of slightly more than 9500 feet. The thickening of

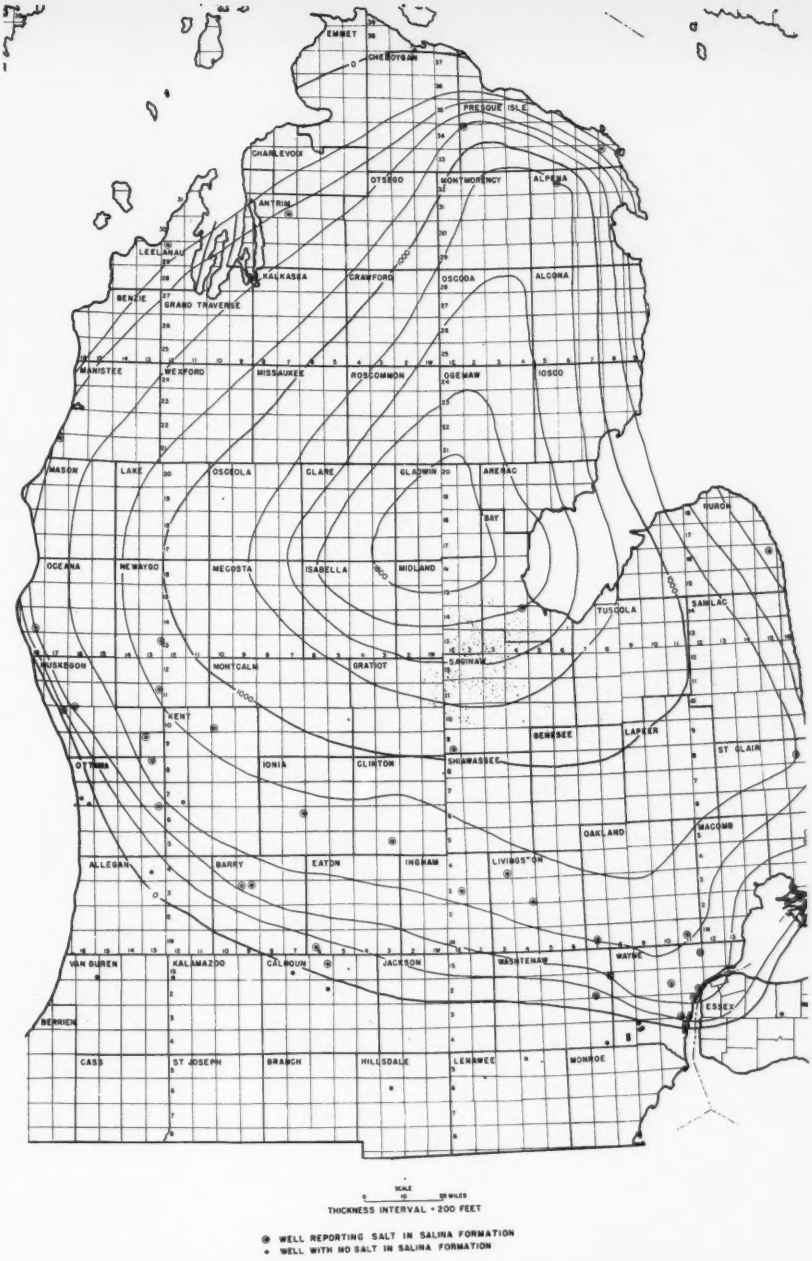


FIG. 3.—Map showing the aggregate thickness of salt in the Salina formation (After Landes, 1945).

the salt toward the center of the basin (fig. 3) combined with the great thicknesses of salt within the basin indicates subsidence of the basin during Salina deposition. It also necessitates the addition of brine during deposition to furnish the great thickness of salt. No seaway through which brine might have been added has yet been identified. Some authors (Dunbar, 1949) place the seaway to the northeast or northwest of the basin although there is no definite evidence of either. Contemporaneous salt and associated gypsum beds are found in eastern Ohio and New York and are probably connected with the Michigan basin beneath Lake Erie between southwest Ontario and Ohio. This presents the possibility of the replenishment of the brine in the Michigan basin through the New York basin.

Most authors agree that the Salina climate was dry (Newcombe, 1932). The postulated conditions of deposition call for a shallow landlocked sea surrounded by a low land mass with bedrock areas of limestone. The replenishment of the water in the basin was apparently intermittent during gradual subsidence of the basin. A delicate balance was maintained between sinking, evaporation, and supply so that at no time did evaporation approach completion.

## THE DEPOSITION OF HALITE AND THE BANDED SALT

### Introduction

The term, "Jahresringe," has long been used to describe the thin laminae of anhydrite or polyhalite found at relatively close but irregular intervals in salt layers. Early workers (Phillips, 1947) attributed this banding to seasonal deposition. However, some opposition to this theory has developed as a result of the discovery of clay laminae of the same general character which are known to have resulted from an influx of sediment charged waters from an adjacent land mass. This example of a change in the nature of the basin waters as a cause of the deposition of the laminae has led to the postulation that the bands of anhydrite and polyhalite are the result of a similar change—perhaps an influx of water from the land mass or an influx of sea water into the basin.

The banded salt is composed of three distinct units (fig. 1): carbonate and sulfate laminae, clear salt, and cloudy salt. The clear salt and the cloudy salt differ in the manner of crystal growth. The cloudy zones are composed predominately of a peculiar type of halite crystal whose shape is outlined by abundant liquid inclusions (fig. 4). The clear areas are relatively inclusion-free. Normally, in the Glen Bradley core the two types of salt are separated into relatively distinct parallel bands. This relationship is not so pronounced in the Detroit mine. There is no regular sequence or ratio of thicknesses between the two salt units and the anhydrite. In the Glen Bradley core the anhydrite bands are separated by 0.4 to 7.5 centimeters of salt. In the Detroit mine the separation may be as much as 30 centimeters. In general, these bands are bounded on both sides by crystals of cloudy salt.

FIG. 4.—Photomicrograph of a thin section showing a pyramidal shaped hopper crystal outlined by brine-filled, negative crystals. The specimen is from the Glen Bradley well core, 264.5 feet above the base of the Salina formation. Core depth—4890.5 feet. Plane-polarized light. ×19.3

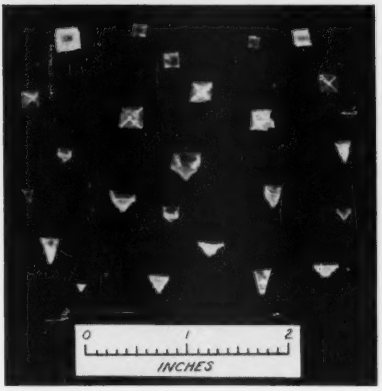


FIG. 5.—Manufactured pyramidal shaped hopper crystals.

## Crystal Growth and Deposition of the Salt

That the growth of halite crystals is initiated at the surface of the brine is a fact long recognized. The surface growth of artificial salt crystals in the manufacture of grainer salt is controlled by conditions not unlike those which might exist in a natural basin. Temperatures in this process (49°–60° C) are in excess of those which might be expected in nature but higher temperatures only tend to accelerate crystal growth, and artificially produced hoppers might be expected to be comparable to natural crystals. Industrial usage defines the crystals produced artificially as hopper crystals. The same term, as used by the mineralogist, generally implies a skeletal cube with depressed faces resulting from the greater tendency toward growth along the edges of the embryo cube. As can be seen in figure 5, the industrial crystals differ in form, and result from an entirely different growth process than that responsible for mineralogical hopper crystals.

In the manufacture of grainer salt (Badger and Baker, 1928) crystal growth is brought about by evaporation at temperatures below the boiling point in order to prevent turbulence and to permit the formation of a thin surface film of high-density brine. In this film the halite crystals begin to grow. As growth continues the cube tends to sink under its own weight, although its position at the surface is maintained by surface tension. Because only one face of the cube is in contact with the high density film, growth takes place only along its edges. In this manner, while the crystal sinks, growth continues upward and outward along these edges resulting in the hollow pyramid with the apex pointing downward (fig. 6). When the surface is disturbed, the crystals are broken or swamped and sink. The crystals are extremely delicate and can withstand very little handling. Occasionally a number of crystals in a small area will become attached to one another to form a crust or mat which will eventually sink as a unit. Similar crystals have been observed in the Salina salt. The crystal form is outlined only by the presence of abundant liquid inclusions in the form of oriented negative crystals (fig. 4). For the most part only fragments of crystals

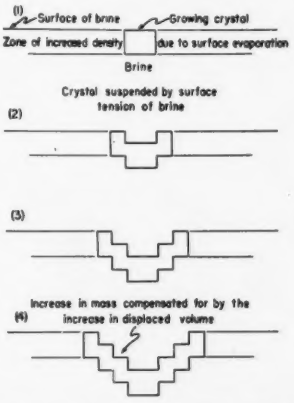


FIG. 6.—Schematic diagram showing in cross section the method of growth of a pyramidal shaped hopper crystal.

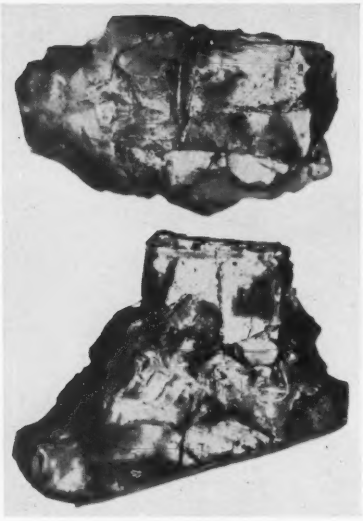

FIG. 7.—A pyramidal shaped hopper crystal contained in an oriented overgrowth of clear salt. In the top view the hopper appears in the lower right hand corner with the apex pointing up. In the bottom view the open end of the pyramidal shaped happer is facing out. The specimen is from the Glen Bradley well, 270 feet above the base of the Salina formation. Core depth—4885 feet. ×3.5.

are to be found. The chevron structure (Dellwig and Briggs, 1952) commonly observed in thin section is merely the result of slicing through the corner or edge of a pyramidal shaped hopper.

The maximum measurement across the open end of a pyramidal hopper is 3.6 millimeters, although the size of some of fragmental crystals suggests that the original pyramidal shaped hopper may have been much larger. In some layers it was noticed that there is an orientation of the pyramidal shaped hoppers over a short distance laterally with the vertices of the pyramids pointing downward. This apparently is the result of settling of a portion of a mat or crust which formed through the intergrowth of several individual crystals on the surface. The cloudy layers or masses are the result of lithifaction of an assemblage (generally lacking orientation) of complete and fragmented pyramidal shaped hoppers which grew at the surface of the brine.

The absence of inclusions is not sufficient in itself for concluding that the pyramidal shaped hoppers are not contained in the transparent salt masses. The development of inclusion-free crystals does, however, strongly suggest crystal growth under different conditions for the clear layers as well as for the isolated clear crystals. Isolation of some pyramidal shaped hoppers enclosed in large masses of clear salt yielded cleavage fragments as shown in figure 7. It is apparent that a crystal of this size could not have grown suspended at the surface of the brine. The overgrowth is in crystallographic continuity with the pyramidal shaped hopper. In some cases more than one pyramidal shaped hopper fragment is included in a single large clear crystal. Apparently some fragments acted as a nucleus for overgrowth whereas others have merely been included during growth.

Additional evidence for the development of syngenetic overgrowths on the

FIG. 8.—Pyramidal shaped hoppers of solar salt. The original hopper which formed at the surface of the brine appears as the dark area of the crystal, and the clear overgrowth appears as the light area. In some of the crystals there is a tendency toward the modification of the hollow pyramid to form a cubic crystal. Natural size.

FIG. 9.—Partly etched section from the Glen Bradley well showing the conformity of the anhydrite in the upper dolomite-anhydrite layer to the underlying halite cubes. The light areas standing out in relief are anhydrite, the dark areas dolomite. The specimen was taken from the Glen Bradley well, 10 feet above the base of the Salina formation, Core depth—5145 feet. Natural size.

pyramidal shaped hoppers can be found in solar salt crystals. Figure 8 shows specimens from two of six sampled localities. In all localities pyramidal shaped hoppers or fragments of pyramidal shaped hoppers are encased in an overgrowth of inclusion-free salt. The crystals are not hollow and it is not possible that surface tension alone could have supported these crystals at the surface of the brine while they grew to this size. The enlargement of the crystals has taken in the bottom of the basin. Not only have the crystals become enlarged, but they have also shown a tendency toward the development of a cube, indicating an entirely different mode of crystal growth.

Figure 9 also attests to syngenetic bottom growth of the salt cubes. The imprint of the cubes of clear halite can be seen in the overlying dolomite and anhydrite, and the undeformed upper surface of the carbonate and sulfate layer attests to the growth of the salt cubes before, or at the latest, during the deposition of this overlying layer. Here again, crystals of this size and form could only be the result of bottom growth.

A further significant feature associated with the pyramidal shaped hopper structures is the absence of crushing or displacement of portions of an individual crystal. At least partial deformation of the pyramidal shaped hopper structure would be expected in the event that this material was subjected to compaction during burial. For the most part the crystals have undergone no deformation. This strongly indicates that little, if any,

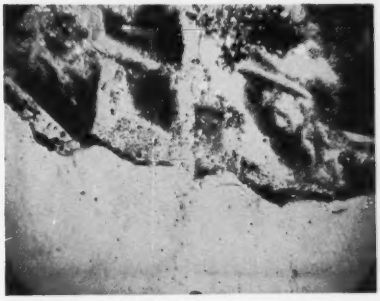

FIG. 10.—Photomicrograph of a thin section showing clear salt separated from pyramidal shaped hopper fragments by an anhydrite lamina. The small grains in the photograph are primarily anhydrite. The large, dark, angular areas are inclusion-rich zones in pyramidal shaped hoppers. The grey background areas are clear halite crystals. The specimen is from the Glen Bradley well, 271.7 feet above the base of the Salina formation. Core depth—4883.3 feet. Nicols partly crossed. ×16.5

pore space existed between adjacent salt grains at the time of burial. Through solution and recrystallization the loose, unconsolidated halite fragments apparently formed a relatively rigid and solid salt mass. Figure 11 shows a typical relationship which is found in thin section study. The angular hopper crystals underlying anhydrite lamina have been beveled, through solution, to form a flat surface on which the anhydrite was deposited. The truncation of the crystals suggests that they were held in a relatively rigid position and that some degree of lithifaction was attained before the development of this surface. Walther (1912), in his description of some present day salt deposits of Mexico, speaks of the salt as being "solid as ice." At the same locality ripple marks were seen developing in this salt crust when the wind moved the overlying water. Ripple marks are also common in the Salina salt in the Detroit area (Kaufmann and Slawson, 1950).

FIG. 11.—Photomicrograph of a thin section showing a sequence of clear salt, pyramidal shaped hopper fragments, an anhydrite lamina, and pyramidal shaped hopper fragments. The dark, chevron shaped areas are inclusion-rich zones in pyramidal shaped hoppers. The linear mass of small, white to grey crystals forms the lamina of anhydrite. The grey background material is clear salt. The specimen is from the Glen Bradley well, 267.4 feet above the base of the Salina formation. Core depth—4887.6 feet. Nicols partly crossed. ×16.5

The data assembled suggest the following process for the deposition of the halite. In a brine-filled basin, growth of the pyramidal shaped hoppers began with evaporation and the formation of a thin film of high density brine. Upon disturbance of the surface the crystals sank. The presence of abundant, flaky crystals soon brought about saturation of the bottom layer of the brine through solution, provided that this condition did not already exist. An increase in temperature changed the saturated brine to an unsaturated condition so that solution of some salt was necessary to reestablish equilibrium. Although the solubility of salt varies but a small amount with temperature, a relatively large amount of salt can be taken into solution with a temperature change if there is a large enough quantity of water. If saturation took place during a warm period, subsequent cooling brought the brine into the metastable condition and growth began around the existing nuclei (Buckley, 1951). These nuclei were fragments of partly dissolved pyramidal shaped hoppers, or crystals which had dropped subsequent to the saturation of the lower layer of brine. This process was responsible for the growth of large crystals tending toward a cubic habit. With the reestablishment of equilibrium at the reduced temperature, newly precipitated pyramidal hoppers settled onto the crust of clear salt. Repetition of this process was initiated by a subsequent rise in temperature, the amount of solution taking place depending upon the magnitude of the rise and the length of time during which temperature continued to increase. Almost without exception the resulting clear crystals are much larger than the original hoppers.

Although temperature changes can account for solution and reprecipitation of the halite, other factors may aid the process. Some solution may result from pressure at the contact between adjacent grains and recrystallization on non-contact surfaces. Extremely small frag-

ments may go into solution causing temporary supersaturation with equilibrium being reestablished by growth around larger more stable fragments.

## Temperature of Deposition of the Salt

The most important single factor in the determination of the temperature of formation by means of liquid inclusions is the separation of primary and secondary inclusions and minerals (Ingerson, 1947). This problem assumes even greater importance in salt deposits because of the ease of solubility of halite in water (Peach, 1949). In salt the determinations of temperature of deposition can be made from the pyramidal shaped hopper crystals in the cloudy layers of salt with more than reasonable assurance that the crystals are primary. There can be little doubt that solution and recrystallization would have completely destroyed the delicate primary structure of the pyramidal shaped hopper crystals.

With the establishment of the formation of the pyramidal hoppers at the surface of the brine and consequently at a pressure of one atmosphere, the problem of the relationship between the pressure of formation and atmospheric pressure is eliminated.

The elimination of this problem, however, is more than compensated for by the greater problem of leakage. In both thin sections and polished plates bubbles in inclusions are abundant, whereas in cleavage fragments bubbles in inclusions are comparatively rare. Apparently the stress of sawing and grinding is sufficient to open cleavage planes and permit the addition of air or some loss of liquid from the inclusions. By use of fragments from 1.5 to three millimeters in thickness and focusing on inclusions well within the fragments, the probability of obtaining unaltered inclusions was increased.

Temperature determinations were made from material from several layers in the salt bed (table 2). Each cleavage fragment was first examined to establish the relationship between the inclusions and a pyramidal shaped hopper crystal. From each layer between 25 and 35 fragments were studied, but in many fragments no suitable inclusions were found.

For comparison, crystals from the Zuni Salt Lake, New Mexico, and manufactured grainer crystals were examined. In these crystals, as in the natural pyram-

TABLE 2.—*Tabulation of temperature determinations from liquid inclusions. The average temperature is determined from both the disappearance of the bubbles with a rise in temperature and the reappearance of the bubbles with the subsequent lowering of the temperature. The maximum variation of temperature in an individual specimen is 3°C. All samples are from the Glen Bradley well*

| Core Depth | Specimen Number | Average Temp. °C | Number of Readings |
|---|---|---|---|
| 4882 feet | 1-1 | 37.0 | 1 |
| | 2 | 48.0 | 1 |
| | 2-1 | 40.0 | 6 |
| | 3-1 | 42.4 | 6 |
| | 4-1 | 43.0 | 6 |
| 4885 | 1-1 | 32.0 | 1 |
| | 2 | 32.7 | 6 |
| | 2-1 | 32.5 | 1 |
| | 2 | 32.1 | 6 |
| | 3 | 40.2 | 6 |
| | 4 | 44.8 | 6 |
| | 3-1 | 33.0 | 1 |
| | 4-1 | 37.9 | 6 |
| | 5-1 | 38.2 | 3 |
| 4891 | 1-1 | 37.8 | 6 |
| | 2 | 36.0 | 1 |
| | 3 | 37.4 | 6 |
| | 4 | 33.0 | 1 |
| | 2-1 | 36.6 | 1 |
| | 2 | 37.8 | 6 |
| 4893 | 1-1 | 47.3 | 6 |
| | 2 | 48.1 | 6 |
| | 3 | 43.1 | 6 |
| | 2-1 | 69.0 | 6 |
| | 2 | 66.0 | 6 |
| | 4-1 | 39.9 | 6 |
| | 2 | 45.9 | 6 |
| 4894 | 1-1 | 47.4 | 6 |
| | 2 | 48.4 | 6 |
| | 2-1 | 43.2 | 6 |
| | 2 | 38.0 | 1 |
| | 3-1 | 39.9 | 5 |
| | 4-1 | 44.5 | 6 |
| 5155 (Base of Salina.) | | | |

idal shaped hoppers, bubbles were found in some, but not in all negative crystals.

The bubbles examined had a maximum diameter of approximately 0.006 millimeter; the inclusions containing them ranged from 0.032 to 0.010 millimeter measured across the cube face.

If the inclusions are primary and the bubbles are the result of the creation of a vacuity owing to contraction of the liquid on cooling, the theoretical ratio between bubble volume and inclusion volume should be constant. It is possible, of course, that the bubbles contain air which was included in the cavity at the time of crystal growth. However, where the size ratio of bubble to void is a constant in several inclusions found together and the temperature at which the bubbles disappear upon heating is similar, it is certain that the bubbles do not represent air inclusions. Moreover, Sorby (1858) observed during the growth of artificial crystals at high temperatures that the inclusion-bubble volume ratio was low when the bubble was of air. In the specimens studied the ratio was high.

Sorby also showed that the adhesive force between the brine and the crystal walls in small inclusions was sufficient to counteract the force of contraction of the liquid and prevent the formation of a vacuity. In the same experiments Sorby demonstrated that crystals exposed to air after growth leaked relatively large quantities of air into the inclusions and large bubbles were abundant. If this is the case, it is reasonable to assume that crystals which are submerged after growth might leak water into the vacuity and fill it in the same way.

In the material under study, many inclusions that originally contained a bubble absorbed the bubble with a temperature rise but failed to release it with the subsequent temperature drop. Apparently in these cases leaks were developed through expansion of the fluid in the cavity and additional fluid was introduced during contraction, perhaps from adjacent inclusions.

The inclusions were studied with a Leitz heating stage at 225 magnifications. The bubbles were measured at room temperature and the temperature was slowly raised until they disappeared. The temperature of reappearance of the bubble was recorded during the decline in temperature. This was repeated three times and the average determined. The scarcity of bubbles suggested a possibility of temperatures of formation below room temperature, but examination of several specimens cooled to below 10° C failed to show the development of any additional bubbles.

The data were determined from approximately 200 cleavage fragments. In the early stage of the investigation all bubbles were examined and temperatures were found to range from 32° to in excess of 100° C. However, by selecting inclusions definitely associated with pyrammidal hopper crystals and located deep within the cleavage fragment (so that the possibility of leakage was reduced), the upper limit was lowered approximately 50° C.

All determinations were made from samples from the Glen Bradley well core. All determinations fall between 32.0 and 48.4° C. Inasmuch as the temperatures were determined from pyramidal shaped hopper crystals, they represent the temperature at the surface of the brine, not the temperature of the entire body of water. Harvey (1925), in making temperature determinations in ocean water 20 miles southwest of Plymouth, England noted that in clear weather with light winds the upper 2.5 to five centimeters became very hot. Atkins (1924) noted that in small ponds the upper two centimeters of water were up to 5° C warmer than the water 20 centimeters deep. Landes (personal communication) observed a similar temperature difference in the uppermost layer of brine in Zuni Salt Lake, New Mexico. It would seem reasonable to expect a steady increase in temperature in this upper few centimeters up to the surface. Inasmuch as these temperatures determined from the

inclusions represent temperatures of the surface film of brine, they then need not indicate temperatures of deposition greatly in excess of present day temperatures in some areas. Ocean temperatures at the surface in subtropic regions are recorded at 27° C, and surface temperatures are recorded in the Mediterranean at 21° C and in the Black Sea at 23° C (Trask, 1939). Ingerson (Dreyer, Garrels and Howland, 1949) reports temperatures of 70° C in a lake near the Caspian Sea.

Some correlative evidence for the determined temperature range is offered by the identification of langbeinite in several sections. Studies by Van't Hoff (1903) establish the minimum temperature for the formation of this mineral at 37° C, a temperature congruous with the range determined by the study of inclusions. The mineral is found as small (about 0.006 mm) anhedral crystals contained within salt crystals.

Although no absolute data are available, generalized observations in the salt ponds in which solar salt is deposited relate grain size to temperature (Buchen, personal communication). Although there are apparently additional unknown factors involved, it has definitely been established that a warm evaporating season produces smaller crystals than does a cold season. The largest pyramidal shaped hopper of solar salt illustrated in figure 8, is several times larger than any found in the Salina salt. This also suggests that somewhat higher temperatures prevailed during the formation of the Salina salt than are found in California solar salt flats today.

In the growth of artificial halite crystals, Kindle (1918) found that above 21° C pyramidal shaped hopper and true hopper crystals are formed, whereas below that temperature the cube is the common form. Although this does not help to establish the temperature of deposition, it does indicate that the surface growth of pyramidal shaped hoppers is favored by high rather than low temperatures.

## Deposition of the Banded Salt

The growth processes of the halite crystals provide an important key to the problem of the depositional relationship between the salt and the anhydrite-dolomite layers.

The structural and mineralogical relationships in the Glen Bradley well core are essentially the same as those in the Detroit mine. The material from the Glen Bradley well should be representative of sediments deposited near the central portion of the basin, whereas the material in the Detroit mine should reflect conditions closer to the shore (fig. 3). In the growth of the halite crystals the variation in environmental conditions was unimportant. However, in the deposition of the laminae of dolomite and anhydrite, variations (as a result of the difference in depth environment) between the two localities are quite pronounced.

### *Central Basin Deposition*

The interval between anhydrite laminae in the Glen Bradley well core varies between 1.5 and eight centimeters; the thickness of the individual lamina rarely exceeds 0.5 millimeter. The halite is generally in the form of either clear or cloudy layers, although intermixing of the two types of salt is not uncommon. The individual lamination is relatively flat and uniform in thickness. About 80 percent of the mineral grains in these layers are less than 0.002 millimeter in maximum dimension and only a small percentage of the remaining 20 percent exceeds 0.004 millimeter.

The laminae are composed primarily of stubby tabular crystals of anhydrite but also contain dolomite, pyrite, quartz, celestite, polyhalite, and carbonaceous material. Anhydrite, pyrite, and polyhalite almost always occur as euhedral crystals.

The individual layers show no vertical gradation of grain size nor segregation into mineral bands. The lack of evidence of any consistent relationship between these layers and either type of salt (clear

or cloudy) necessitates a cause of deposition entirely independent of the causes of the original growth or the solution and recrystallization of the halite. Although there are significant relationships common to each layer, the salt surfaces of deposition and the layers themselves show considerable variation.

*Structure.*—Some relationships within the laminae and between the contacts separating the laminae and the enclosing salt are shown in figures 10 through 13.

Figure 10 shows a lamina that attains a maximum thickness of about 0.5 millimeter. The salt below the layer is clear salt and that above is composed of pyramidal shaped hopper crystals separated from one another by contemporaneously crystallizing anhydrite.

A similar relationship is shown in figure 11 except that several pyramidal shaped hoppers have settled onto the clear salt layer prior to the precipitation of the anhydrite. The truncation of the upper portion of the crystals and the filling of the interstices with anhydrite suggest that solution took place prior to the precipitation of the anhydrite.

Extreme irregularity of the underside of a lamination due to control of the depositional surface by the angularity of the pyramidal shaped hoppers is shown in figure 12. In this specimen the pyramidal shaped hoppers have not been subjected to solution prior to the deposition of the anhydrite so that the bottom surface of the layer has a saw-tooth structure. A similar type of irregular surface of deposition is shown in figure 9 where the irregularity is caused by well developed cubes of clear salt. Whether this irregularity is caused by pyramidal shaped hoppers or cubes of clear salt, it is indicative of deposition of a particular lamina without prior solution of the bottom crystals.

In present day natural salt deposits and also in solar salt pans some degree of consolidation takes place even before burial under subsequent layers. Some evidence of similar lithifaction in the Salina salt is shown by the manner in which rigidly supported crystals are beveled to form a flat surface of deposition for the layer above. Figure 13 shows immediately above the beveled surface about 0.1 millimeter of clear salt whose growth apparently preceded and in part was contemporaneous with the deposition of the overlying pyramidal shaped hoppers.

The microfaulting is best attributed to compaction because deformation of salt under pressure would result in flowage rather than in faulting of the salt. The faulting might also be accounted for by recrystallization but there is no evidence of this.

For the most part, although the over-all appearance is suggestive of uniformity, many of the laminations are irregular and discontinuous.

*Mineralogy.*—The most significant feature of the banded salt is the association of pyrite and carbonaceous material with one another and their localization along the anhydrite-dolomite laminae. The pyrite commonly occurs as euhedral

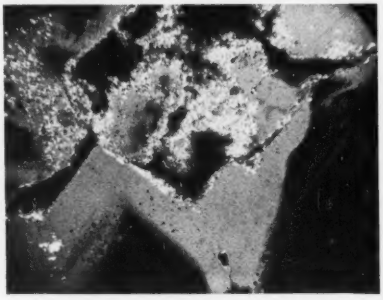

FIG. 12.—Photomicrograph of a thin section showing the control of the deposition of an anhydrite lamina by angular pyramidal shaped hoppers. The grey and black chevron shaped areas are the hopper crystals of halite above which has been deposited the anhydrite (fine-grained, grey to black) intermixed with and overlain by halite (light grey). The specimen is from the Glen Bradley well, 263.6 feet above the base of the Saline formation. Core depth—4891.4 feet. Partly crossed nicols. ×16.5

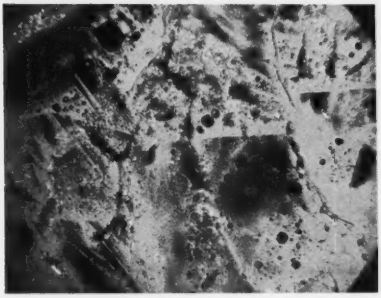

FIG. 13.—Photomicrograph of a thin section showing a faulted contact. Immediately above the flat solution surface (arrows) is approximately 0.1 millimeter of clear salt. Above this have been deposited pyramidal shaped hopper crystals contemporaneous with the anhydrite. The anhydrite lamina is composed of a series of discontinuous masses. The light grey areas are clear salt and the black chevron shaped areas are bands of liquid inclusions. The fine-grained, white to dark grey crystals are anhydrite. The specimen is from the Glen Bradley well, 264 feet above the base of the Salina formation. Core depth—4891 feet. Partly crossed nicols. ×16.5

to subhedral pyritohedrons. Irregular masses are often found occasionally covered with radiating needles of pyrite. Although most of the pyrite is associated with anhydrite-dolomite laminae, a few crystals are contained within the salt layers. It is apparent that the pyrite is genetically associated with the laminae. Those crystals contained within the salt probably settled out of the newly deposited anhydrite-dolomite lamina into the underlying salt. On the other hand, iron in the form of hematite is confined to the salt layers, occurring as either dust-like inclusions or as extremely fine dendritic masses.

The explanation for the iron in the form of pyrite can be found in the association of carbonaceous material with the laminae which would indicate a reducing environment. Carbonaceous material has been reported in the closely related Salina salt of New York (Alling, 1928). However, Alling indicated no specific mineralogical association and the irregular shape of the fragments prevented the determination of their origin.

Fragments of the carbonaceous material are for the most part in the form of hollow tubes. The tubes have a diameter of approximately 0.0195 millimeter and range in length up to 0.18 millimeter depending upon how the fragments broke during separation. The walls of the tubes are relatively thin. The fragments were examined by Professor Chester Arnold of the University of Michigan who stated that there can be little doubt that they are plant material. Although positive identification could not be made, it was suggested that they closely resemble the large tubes of *Prototaxites*—a Devonian and Silurian plant of questionable terrestrial or marine origin (Arnold, 1952).

Substantiating evidence of the association of organic material with these layers is the petroliferous odor detected in a fresh break through one of the laminae, a feature not uncommon in salt deposits. The odor is not found, however, in the salt layers. Several factors suggest that the inclusion of the petroliferous hydrocarbons took place at the time of deposition. Organic carbon is found in these layers. The migration of the hydrocarbons along laminae less than a fraction of a millimeter in thickness, and often discontinuous, is highly improbable.

Anhydrite occurs primarily as stubby, rectangular, euhedral to subhedral crystals generally less than 0.002 millimeter in length. For the most part, the crystals are oriented with their long axes parallel to the bedding.

Dolomite crystals are sparsely scattered through the anhydrite laminae. The crystals show a wide range in shape, varying from well developed rhombohedrons to rounded crystals with a circular cross section. The crystals are pale red-brown in color and often contain a nucleus of a black, dusty material.

Polyhalite is found as isolated individuals in the salt layers and along the

marginal areas of laminae and isolated pods. It occurs either as acicular prisms or as rectangular crystals with the latter pseudomorphic after anhydrite. It has not been found with the relict crystal form of the gypsum. The size of the crystal varies little from that of anhydrite (for the most part less than 0.002 millimeter).

Carnallite occurs as rounded or pitted grains or as well developed euhedra. It is found either scattered through, or concentrated in zones in the halite crystals (Lucas, 1954).

Gypsum is usually found concentrated in small circular shaped areas in the salt bands and less commonly in small vein-like zones. Both the circular areas and the vein-like zones transect the halite crystal boundaries. The localization and concentration of gypsum in such restricted zones which intersect the halite crystal boundaries indicate that the gypsum is secondary.

Some isolated grains of gypsum are found in the salt bands and, although the temperature range and salinity at the time of deposition may have been favorable for the deposition of the hydrous sulfate, it does not seem possible that it would survive as such in the dense bottom brine. These crystals too are most likely secondary and may have formed as late as at the time of drilling.

Whether or not any of the calcium sulfate was originally deposited as gypsum cannot be determined for no pseudomorphs were found. However, Hollingworth (1948) points out that slow deposition and burial of primary gypsum (given sufficient time to react with the denser bottom solutions) gives rise to secondary anhydrite that is difficult to distinguish from primary anhydrite. As a result all evidence of primary gypsum may have been removed.

Quartz is common, both as doubly terminated euhedral crystals and as aggregates of anhedral crystals commonly in the form of rosettes. Most of the quartz is associated with the anhydrite-dolomite laminae, but a genetic relationship to these bands is not clear. The anhedral crystals are generally between 0.004 and 0.008 millimeter in length and the aggregates may be several times larger.

*Summary.*—Several generalizations regarding the deposition of the banded salt are summarized as follows: (1) There is no uniform or cyclic relationship between anhydrite-dolomite laminae and the cloudy or clear salt. The depositional surfaces at the base of the laminae vary from a smooth surface developed through solution to a highly irregular surface resulting from random orientation of either angular pyramidal shaped hopper crystals or recrystallized cubes. The depositional surface is underlain by either pyramidal-shaped hoppers or clear, inclusion-free halite. (2) The confinement of carbonaceous material and an associated petroliferous odor to the laminae, plus the concentration of pyrite along these layers (as opposed to the association of hematite with the salt bands), point to an influx of water into the basin as the cause of deposition of the laminae. As a result of the influx reducing conditions are established in the basin with a change in the Eh value from $+0.1$ for the deposition of the halite to $-0.3$ for the deposition of the anhydrite-dolomite laminae (Krumbein and Garrels, 1952).

Replacement has been limited and the sequence is as follows: (1) Gypsum was replaced by anhydrite. (2) Anhydrite was replaced by polyhalite. (3) Halite was replaced by gypsum.

### *Marginal Basin Deposition*

*Structure.*—Although there is a general similarity of structure in the banded salt in the Glen Bradley well and the Detroit mine, megascopic examination reveals several pronounced differences between the salt deposited in the central portion of the basin and that deposited nearer shore.

One of the most pronounced differences is the absence or poor development of

banding of clear and cloudy salt at the Detroit mine. In most instances banding is completely absent and the entire salt mass shows a relatively uniform degree of translucency. In several specimens the banding is poorly developed; in no specimen is banding as well developed as in the Glen Bradley core.

Another pronounced difference is that the anhydrite-dolmite layers at the Detroit mine generally are thicker and more widely spaced than in the Glen Bradley core, and intervals between adjacent bands of eight to 10 centimeters can be found throughout the mine workings. Dolomite and anhydrite appear to be more abundant and this is substantiated by analyses of representative samples. Pyrite associated with these laminations is also more abundant and occurs in larger masses than in the Glen Bradley core. It is also found in a lesser quantity scattered throughout the salt bands.

The anhydrite-dolomite laminae are not only more prominent near the basin margin, but the bedding is undulating, although it is apparent in a wall or face that the average distance between adjacent laminae does not vary (figs. 1 and 14). In some areas the undulation in the individual layer may be attributed partly to ripple marks. Ripple marks are almost continuous along several laminae and are found intermittently associated with a number of other laminae.

Microscopic examination reveals that the salt from the basin margin contains fewer pyramidal shaped hopper crystals and more clear salt than does the salt from the central part of the basin. Fragmentation of the pyramidal shaped hoppers has been extensive and complete hoppers are not found. The increased percentage of clear salt suggests a greater amount of bottom solution and recrystallization. As in the Glen Bradley core, there is no apparent genetic relationship between the clear or cloudy salt and the anhydrite-dolomite laminae.

The environmental differences of deposition are further expressed in the laminae by variations in grain size and crystal form, by more pronounced replacement and recrystallization, and by layering within the individual laminae. Specimens from the mine workings are layered in two distinct ways. Dolomite crystals contained within layers of anhydrite are segregated into poorly developed bands, or the anhydrite layers may be separated into several thin laminae by dark bands of iron oxide (?). The anhydrite adjacent to these bands is commonly oriented with its long axis parallel to the bedding. The layering of the dolomite may suggest fluctuation in conditions of deposition or, along with the orientation of the anhydrite crystals and the layering by films of iron oxide, it may indicate a degree of sorting and orientation of the crystals by bottom currents. Some weight is given to this conclu-

FIG. 14.—Typical banded Salina salt from the Wabash area of the Detroit mine of the International Salt Company. The black areas are predominately anhydrite and the white and grey areas are halite. The specimen comes from approximately 666 feet above the base of the salina formation. Mine depth—about 1140 feet. ×0.5

sion by the persistent association of ripple marks with the laminae. Two thin sections through ripple marks show some degree of orientation of the anhydrite grains and the development of a crude layering by the films of iron oxide.

In the thick anhydrite-dolomite layers in the mine it is often observed that a layer is composed of distinctly separated bands of dolomite and anhydrite. In some specimens the relationship between a pair or series of bands cannot be explained reasonably by any postulated set of physical-chemical conditions of deposition. However, fragments of halite scattered throughout the thick anhydrite-dolomite layer can be identified as pyramidal shaped hopper crystals and appear to represent remnants of a layer of halite which has been removed through solution. Complete solution of thin salt layers could in this way give rise to anomalous relationships which are not the result of changing physical-chemical conditions.

More commonly, however, a layer of anhydrite and dolomite acts as a cap for the underlying salt and retards or prevents its solution. Retardation of solution in this manner has been observed by Grossman (1949) in the sodium sulfate deposits in western North Dakota.

*Mineralogy.*—In contrast to the stubby, rectangular anhydrite crystals from the Glen Bradley core, the anhydrite from the Detroit mine is usually found in the form of needle-like crystals and to a lesser extent as crystals with the crystal form of gypsum. About 60 percent of the needles are between 0.008 and 0.016 millimeter in length. The long axes of those crystals with the crystal form of gypsum generally measure between 0.004 and 0.008 millimeter, although some of the crystals are considerably larger.

The needle-like crystals occur in interlocking mats or laminae of primary origin, as unoriented individuals replacing halite, in radiating groups of crystals in the salt adjacent to the anhydrite-dolomite laminae, or as bursts of large crystals radiating from a central mass of fine-grained anhydrite. Large crystals radiating from a fine-grained nucleus have been attributed by Dunham (1948) to replacement of anhydrite by halite and concomitant recrystallization of the anhydrite. The needle-like form may, therefore, be of either primary or secondary origin.

Anhydrite pseudomorphs after gypsum are generally found either in the marginal areas of the laminae or as isolated crystals contained within the salt. The replacement is usually complete, although in some crystals remnants of gypsum can be found. The crystals are rarely entire and deeply etched boundaries show replacement by halite. The replacement is almost entirely confined to the gypsum pseudomorphs; in some cases all that remains of the crystal is a group of several fragments roughly outlining the original gypsum crystal form and having the same optical orientation.

It should be pointed out again that the presence of pseudomorphs after gypsum in the Detroit mine, in contrast to their absence in the Glen Bradley core, need not indicate a difference in the temperature or salinity between near shore and off shore environments of deposition. It may rather be merely a reflection of the rate of precipitation and speed of burial of the gypsum. Rapid precipitation and burial of gypsum will result in the replacing anhydrite retaining the crystal form of the gypsum.

Pyrite is found in increased amounts in the mine specimens and primarily as large, irregular masses rather than as euhedral crystals. Some of these masses are in excess of 0.5 millimeter in diameter. The pyrite is not confined as closely to the anhydrite layers as in the specimens from the Glen Bradley well, but the concentration of a large percentage of the grains adjacent to the layers again indicates this genetic relationship. On the other hand, little carbonaceous material is found and the

fragments are irregular in shape. It is confined primarily to the anhydrite-dolomite laminae.

Dolomite is more abundant in the Detroit mine than in the Glen Bradley well and is largely concentrated in crude, discontinuous layers. The crystals are anhedral to subhedral, brown in color, and some contain a nucleus of black, dusty material. The character of individual grains and their relationship to anhydrite strongly resembles the material described from the Permian of England (Dunham, 1948; Stewart 1949, 1951a, 1951b, 1953). The occurrence of the dolomite in nearly spherical grains is attributed by Dunham (1948) to a change in composition of the brine before completion of the crystallization of the carbonate. The dark centers found in many of the grains possibly acted as seeds, initiating the crystallization of the dolomite.

An alternate explanation is that the dolomite, at least in part, might be clastic in origin. The low, barren land mass adjacent to the basin exposed carbonate rock and the climate was arid. It seems more than reasonable that some carbonate would be carried into the basin by the wind or by intermittent land drainage. The sphericity of the grains could easily be the result of transportation in this manner.

Unfortunately, the differentiation between clastic and precipitated carbonate becomes difficult if dolomitization (Pettijohn, 1949) and lithifaction (Hatch and Rastall, 1938) have occurred. The existence of almost ideal conditions for the formation and transportation of clastic carbonate, the increase in the percentage of carbonate in the salt nearer the margin of the basin, and the sphericity of the grains suggest in part a clastic origin. On the other hand chemical precipitation is favored by the individual grains being composed of a single crystal, the presence of dusty inclusions in the center of the grains, and the confinement of the grains to the vicinity of the dolomite-anhydrite laminae.

A small number of dolomite grains have been found which contain cores of calcite, this indicating that at least some of the dolomite has resulted from the replacement of calcite. Not uncommon are ring shaped fragments of dolomite, in which the central portion has been replaced by halite. This suggests a differential replacement of the carbonate although there is no indication of the cause or manner of the replacement.

Although calcium sulfate was deposited in the form of both anhydrite and gypsum, little gypsum has survived the replacement by anhydrite. The gypsum is found only as remnants in anhydrite crystals. However, as in the Glen Bradley core, a later generation of gypsum has replaced halite. The crystals are generally euhedral, and are only a fraction of the size of those of the first generation. They are also confined to restricted and generally circular areas in which there is a higher concentration of sulfate than in the surrounding salt.

Polyhalite is relatively rare. The individual grains have retained the original crystal form of the gypsum. The replacement sequence is gypsum-anhydrite-polyhalite.

*Summary.*—The poor development of bedding or its non-existence in the clear and cloudy salt, fragmentation of the pyramidal shaped hopper crystals, and abundant ripple marks are all suggestive of some degree of turbulence in the marginal areas of the basin. With this turbulence would come repeated vertical mixing of the brine, with subsequent changes in the composition of the bottom layer of the brine causing destruction of the conditions of equilibrium at the depositional interface. In deep water rain and light winds do not suffice to intermix the upper and lower density zones (Harvey, 1925). However, in shallow water meteoric conditions might frequently destroy density zoning.

The halite crystals initially grow as pyramidal shaped hoppers, but, through

turbulence and intermixing of the upper and lower density zones, they undergo fragmentation and solution to a greater extent than do those crystals deposited in the deeper waters of the basin. However, the persistent occurrence of the hopper fragments in the salt column indicates that the brine maintained a relatively high concentration even with vertical mixing.

Gypsum and anhydrite were both deposited as primary minerals although gypsum was extensively replaced by anhydrite and to a lesser degree by halite.

It is probable that the carbonate was deposited both as a clastic and as a chemical precipitate.

The complex replacement sequence in these marginal basin evaporites appears to have been as follows: (1) Calcite was replaced by dolomite. (2) Gypsum was replaced by halite. (3) Gypsum was replaced by anhydrite. (4) Anhydrite was replaced by polyhalite. (5) Anhydrite was replaced by halite with attending recrystallization of anhydrite. (6) Dolomite was replaced by halite. (7) Halite was replaced by gypsum.

These observations point to more, and more rapidly developed, differences in the composition of the solution near the margin of the basin. No difference, however, is indicated for the basic principles of deposition.

## THE THEORETICAL ASPECTS OF DEPOSITION

With the many advances that have been made in physical chemistry and marine research, it would seem that the development of any theory of salt deposition would be rigidly controlled by experimental or observational data. However, certain conditions of deposition that are known to have existed must be carefully considered in the evaluation of experimental data.

One of the most important factors commonly neglected in laboratory experiments is that evaporation in a basin takes place by means of solar heat from above. Solar heating is likely to establish density and temperature stratification in the water during the warm seasons of the year. Heating of the brine from the bottom, however, sets up convection currents which prevent the establishment of stratification in the brine—an extremely important consideration in salt deposition. Stratification exists in both closed basins and the open ocean (Birge, 1910; Birge and Juday, 1922; Atkins, 1924; Harvey, 1923, 1925). Not only is the mass of water divided into a dense lower and a less dense upper unit, but in the upper layer the top few centimeters form a zone which is at a measurably higher temperature than the water immediately below. The seasonal changes of temperature and the alternation of density stratification with homogeneity causes changes in the degree of saturation of the brine and this in turn results in the alternation of crystal growth and solution. Indeed these conditions are extremely difficult to duplicate in the laboratory.

An equally important consideration is the means by which water is replenished in the basin. Not only does this addition change the concentration of salts in the basin, but the manner of addition (as a thin surface layer flowing over and blanketing the denser brine below) causes an abrupt change in the conditions of deposition. This would be true not only for the addition of sea water to the basin but also for the addition of water from the land mass. Although the quantities of terrestrial water added to the basin may be small, the pronounced differences in composition between waters draining from a sedimentary area (Rankama and Sahama, 1950) and the waters of the basin would cause a local change in the chemical composition of the brine in the basin (Mitchell and Solinger, 1934). If the level of the brine in the basin were high, the runoff from the land might be fresh, but if the level of the basin were low it would probably become saturated with

sodium chloride as it flowed over exposed salt flats along the margin of the basin. The small quantities of terrestrial water should not have any widespread effect on deposition of salts in the basin. The addition of rain water would not disturb the stratification in the basin but would merely cause a temporary interruption of precipitation.

Much experimental data have been gathered from a study of a single salt in solution. In other investigations a combination of two or more salts is considered. In either case the effect of almost continuous changes in composition of at least the surface layer, in which crystal growth is initiated, is unknown. Were all of these factors considered, the effect of the numerous trace elements in the brine would still be an unknown factor.

The review of these considerations has been presented to point out the variables in a natural basin which cannot be accounted for in theoretical investigations. Nevertheless, interpretation of laboratory investigations can offer much to the development of the depositional history of the salt.

## Deposition of the Salt

The composition of the sea water and the rate of evaporation are the two basic problems in the deposition of the Salina salt. The composition of sea water during geologic time was subjected to comprehensive study by Rubey (1951). From his discussion it seems most reasonable to assume that the composition of the sea water at the time of Salina deposition was essentially as it is today.

The most important consideration in the rate of precipitation is whether evaporation is of normal sea water or whether it is of brine concentrated to the point of saturation for sodium chloride. In table 3 are shown some of the higher rates of evaporation throughout the world. Also are shown the amounts of salt that would theoretically be deposited if this evaporation were of normal sea water as contrasted with the evaporation of brine concentrated to about one-tenth the original volume, at which point

TABLE 3.—*Average annual evaporation in areas of high rates of evaporation and the amount of salt precipitated (theoretical) during the evaporation of normal sea water as compared to saturated sea water. Data regarding the rates of evaporation modified from Shaw (1928)*

| Locality | Period of Observation | Annual Evaporation in cm. | Salt deposited from: Normal brine in cm. | Salt deposited from: Brine concentrated to saturation point |
|---|---|---|---|---|
| U.S. | | | | |
| New Mexico | 1919–23 | 234.6 | 3.23 | 33.95 |
| Yuma, Ariz. | 1921–23 | 303.9 | 4.18 | 43.97 |
| Mediterranean | | | | |
| Jerusalem | 3 years | 268.0 | 3.69 | 38.78 |
| Jericho | 1924–25 | 329.0 | 4.52 | 47.61 |
| Mexico | | | | |
| Zacatecas | 1907–11 | 308.9 | 4.25 | 44.70 |
| Oaxaca | 1907–08 | 320.6 | 4.41 | 47.30 |
| Australia | | | | |
| Cue, W.A. | | 396.0 | 5.45 | 57.30 |
| Africa | | | | |
| Sidi Barrani, Egypt | 1910–15 | 228.0 | 3.14 | 32.99 |
| Merows, A. E. Sudan | 1905–20 | 599.0 | 8.24 | 86.68 |
| Tokar, Red Sea | 1913–20 | 464.0 | 6.38 | 67.14 |

halite begins to crystallize. The latter figure represents the rate of deposition only when normal sea water ceases to be supplied to the basin and the entire basinwater is saturated with respect to sodium chloride. However, before the saturation point for sodium chloride is reached all the calcium carbonate is removed.

Calculations using the data in table 4 for the salts $Fe_2O_3$, $CaCO_3$, and $CaSO_4$ indicate that these salts should total 4.4 percent of the solids precipitated. In the Glen Bradley well a 15 foot channel sample in the upper portion of the lowest salt layer contained only 0.29 percent insolubles which would include dolomite, anhydrite, pyrite, hematite, quartz, and celestite. In the Detroit mine similar analyses also give only a fraction of 4.4 percent insolubles. These figures must indicate the deposition of a large percentage of the salt from a concentrated brine (the carbonate and the sulfate having been deposited earlier in the history of the basin) or the removal of the greater percentage of the carbonate and the sulfate before entrance of the brine into the basin. This would, perhaps, necessitate the existence of conditions similar to those postulated by Branson (1915) in his modified bar hypothesis. Under these conditions the brine must be concentrated to at least 3.35 times its original concentration (at which calcium sulfate begins to precipitate) so that calcium sulfate might be precipitated (Posnjak, 1940) prior to the transfer of brine to the basin of salt deposition.

TABLE 4.—*Percentages of solids laid down in the evaporation of sea water. Modified after Clarke (1924)*

| Compound | Volume of unit volume of sea water |
|---|---|
| $Fe_2O_3$ | .0030 |
| $CaCO_3$ | .1172 |
| $CaSO_4$ | 1.5642 |
| NaCl | 29.6959 |
| $MgSO_4$ | 2.4787 |
| $MgCl_2$ | 3.3172 |
| NaBr | .5524 |
| KCl | .5339 |
| Sum | 38.2628 |

Some light is thrown on the subject from the combined thickness of a band of clear and a band of cloudy salt. In the Glen Br: Jley core a pair of bands measure between two and nine centimeters which would suggest that, under arid conditions, the evaporation of normal sea water could account for thickness of this magnitude (table 3). It must be remembered that these measurements give only a rough estimate of the thickness of salt deposited in one year because: (1) a single season of extremely high temperatures may bring about the solution of salt deposited during several previous seasons; (2) a period of severe storms and wave action may completely disrupt the density stratification; and (3) the effect of addition of brine to the basin would vary considerably with the season during which it was added. Nevertheless, in the production of solar salt in California, about 11.5 to 12.5 centimeters of poorly consolidated salt are deposited from concentrated brines at a rate of evaporation of about 150 centimeters per year. This represents evaporation under conditions of controlled concentrations, for as soon as the brine reaches the concentration at which magnesium chloride begins to precipitate, the liquor is removed and the pan filled with new brine. Regardless of these conditions, a comparison with theoretical values indicates that less salt was deposited annually than should be expected.

From the above observations, a low percentage of insolubles apparently indicates evaporation from a concentrated brine, and the thin bands of salt indicate evaporation from the surface layer of normal sea water. This is based on the assumption that a high rate of evaporation prevailed. These two apparently divergent facts are compatible, however, if consideration is given to the effect of

the concentration of the salts in solution upon the rate of evaporation. Lowengart (1928) has shown in the evaporation of water from the Dead Sea that, with the continued concentration of salts, there is a decrease in the rate of evaporation accompanied by an increase in temperature until the brine is concentrated to about 1.8 percent of the original volume. At this point all of the energy supplied causes a continued rise in temperature. In this way, the evaporation of a brine, which has been concentrated to the point of saturation, can be shown to produce only a relatively thin layer of salt. At the same time, it may also produce a higher-temperature mineral assemblage than might normally be produced under a given set of climatic conditions (Fulda, 1924).

### Deposition of the Calcium Sulfate and Carbonate

The conditions governing the deposition of $CaSO_4$ have been studied in some detail by Posnjak (1938, 1940) and Hill (1937), and their conclusions in no way conflict with the geologic evidence. Deposition of anhydrite rather than gypsum has been shown to take place at temperatures above 42°C regardless of the concentration of sodium chloride in the solution; and if sea water is concentrated to 4.8 times its original concentration (at a temperature of 30° C), anhydrite will be deposited. Although no data are available, it is to be expected that as the concentration of sodium chloride increases in the evaporating basin there is a corresponding decrease in the gypsum-anhydrite transition temperature. Thus primary anhydrite might be deposited at temperatures below 42° C before the brine concentration approaches 4.8. However, it would be expected that a large percentage of the calcium sulfate would be deposited as gypsum before the concentration of sodium chloride in the brine reached the point where anhydrite would be the stable phase, for it is highly improbable that a temperature of 42° C or more would be maintained in the brine for an extended period of time.

A comparison with solar salt deposition in California (under milder conditions than postulated for Salina time) shows that the majority of the sulfate is removed in the form of gypsum before the deposition of salt begins. Taking all facts into consideration, calcium sulfate should be expected to be found deposited as both gypsum and anhydrite. Just how much is deposited as gypsum cannot be determined for it would be replaced by anhydrite in the denser brine in the bottom of the basin, and under certain conditions of replacement secondary anhydrite cannot be distinguished from primary anhydrite.

Dolomite crystals associated with the laminae offer little evidence with regard to their origin. A few crystals have been found with calcite cores which indicate replacement. Van Tuyle (1916), Mitchell (1923), Linck (1937), and many others have presented evidence favoring the formation of dolomite as a replacement product of calcite rather than as a primary precipitate.

Although the dolomite-anhydrite layers are attributed to an influx of water, the alternation of the laminae of dolomite and anhydrite has not been entirely accounted for. Detailed observations have been made concerning the precipitation of the carbonate (Johnston and Williamson, 1916; Revelle, 1934; Trask, 1937; Wells, 1915), and it has been demonstrated that either increased salinity or increased temperature will cause a decrease in carbonate solubility. In general it is considered that the temperature effect is the more important of the two (Trask, 1937). In spite of the fact that detailed observations have not been made, it is known that increased salinity or increased temperature also cause a decrease in solubility of calcium sulfate. For the same degree of change, however, the effect is not as great for calcium sulfate as it is for calcium carbonate. If,

therefore, the concentration of the brine were at such a point that both the carbonate and the sulfate were being precipitated, carbonate precipitation might be favored during warmer seasons and sulfate precipitation during colder seasons.

## Development of the Basin

Apparently the deposition of the banded salt can take place only after certain conditions have been established in the basin. The main mass of the brine must be concentrated to a point at least near saturation so that most of the dolomite and anhydrite deposited with the banded salt would come from the inflowing water which is intermittently added to the basin.

Before the saturation point for sodium chloride is reached, all of the calcium carbonate and about 90 percent of the calcium sulfate are precipitated in that order. Underlying the salt, therefore, a layer of dolomite overlain by a layer of gypsum and/or anhydrite is normally expected. This sequence should be expected only if a large mass of water became completely isolated and was depleted of carbonate and sulfate before any additional brine was added. On the other hand, if a basin developed through a series of small subsidences, a somewhat different set of conditions might result. If, through subsidence, a relatively small amount of brine entered the basin, it might reach the saturation point for sodium chloride and some salt would be deposited. With further subsidence more brine might be added, again reaching the saturation point for sodium chloride, and additional salt would be deposited. In this way a sequence would develop with several centimeters of dolomite and anhydrite (dependeng upon the amount of brine added) alternating with a greater or lesser thickness of halite depending upon the time lapse before the next influx of brine.

Although the lower portion of the lowest salt bed in the Salina formation from Glen Bradley well is recrystallized, an alternation of bands of dolomite and anhydrite with halite can be observed. In the Delray core from Wayne County, Michigan, the same relationship is observed near the bottom of a thick salt layer. Dolomite and anhydrite bands, one to three centimeters thick, alternate with bands of salt approximately five centimeters thick. These layers might be considered to represent not only periods of influx of brine but also periods of subsidence in the development of the basin.

It is recognized that these observations are very much limited and that exceptions can be found in the sequence in the basin. Basically, however, the conclusion appears sound. If an individual lamina represents an influx of water, a thick layer of the same material should represent an influx of a large mass of water which is accomplished by the depletion of the water in the basin or by the enlargement of the basin. In this case, a sinking of the basin is required to account for the accumulation of a large quantity of concentrated brine from which the thick salt beds will be formed. The deposition of salt directly on the underlying Niagaran rocks might be explained in several ways.

With the concentration of the initial mass of sea water the submerged portion of the basin will contract. The small quantity of dolomite and possibly anhydrite left on the emergent marginal areas may be removed by one of several agents and leave exposed the underlying Niagaran rocks. Although, with an influx of sea water into the basin, there is a tendency for this less dense brine to ride over the more concentrated brine already in the basin; in the marginal areas distant from the point or points of entrance the level of the concentrated brine should rise due to hydrostatic adjustment. In these areas the brine would have been depleted of carbonate and part of its sulfate and salt would have been deposited on the underlying rock.

In addition, the combined effects of turbulence with intermixing of the added brine with the underlying brine and evaporation would increase the density of the brine as it moved across the basin from the entrance point.

Not to be overlooked is the possibility of subsidence in a marginal area permitting the flooding of the area without the addition of brine to the basin. In this way also salt would be the first mineral to be deposited from a brine already saturated with sodium chloride.

## SUMMARY AND CONCLUSIONS

The deposition of the Salina salt has resulted from the evaporation of brine in a semi-closed basin and in an arid or semi-arid region. The addition of brine was apparently intermittent, and there is no evidence of cyclic repetition. Chemically the solution had a pH value of about 8.0 with an Eh value shifting from $+0.1$ to $-0.3$ with the influx of water into the basin.

Thick beds of anhydrite and/or gypsum are absent below the salt beds. In the lower portion of the salt layers thick bands of anhydrite and dolomite alternate with layers of salt of about the same thickness. These thick bands represent not only periods of influx of brine into the basin, but possibly periods of subsidence during which large quantities of added brine are nearly depleted of calcium carbonate and calcium sulfate. Thus a large volume of concentrated brine accumulated. Occasionally the brine reached the saturation point for sodium chloride before more brine was added, and some salt was deposited. Within these thick layers the alternation of laminations of dolomite and anhydrite suggests seasonal banding. The deposition of the dolomite was retarded during the colder seasons and accelerated during the warmer seasons when the solubility was lowered.

Once the basin became more or less tectonically stable and accumulated a large volume of saturated brine, continued evaporation caused the deposition of alternating bands of clear and cloudy salt. This deposition was occasionally interrupted by the addition of new brine to the basin resulting in deposition of anhydrite and dolomite laminae.

The alternation of bands of clear and cloudy salt is a seasonal function. During the warm periods halite, which is precipitated from the surface as pyramidal shaped hopper crystals, may go into solution so that a saturated, dense brine is developed on the bottom of the basin. Deposition of halite, after the establishment of equilibrium between halite crystals and the solution, then form a layer of cloudy, pyramidal hopper crystals. On cooling the brine becomes supersaturated and crystal growth takes place around hopper nuclei. Thus layers of pyramidal shaped hopper crystals represent deposition at which time the bottom layer of brine is saturated with sodium chloride, and layers of clear salt represent crystallization from a supersaturated brine due to a drop in temperature. This cycle may be interrupted by the addition of brine to the basin or by periods of unusual climatic conditions.

The deposition of the anhydrite-dolomite laminae is completely independent of the deposition of the salt, and it may be considered to be the result of the influx of brine to the basin. Indicative of this influx are carbonaceous material, pyrite, a petroliferous odor and the lack of uniform relationships between the banded salt and the anhydrite-dolomite laminae. Although the only carbon to be identified is of plant origin, some may be of animal origin. The addition of brine to the basin as a surface layer would permit the maintenance of life in this brine until the concentration reaches the point when mass extermination takes place, and the subsequent decomposition of the remains would cause reducing conditions to develop in the bottom of the basin. Iron associated with the halite layers is in the form of hematite, indicating that oxidizing conditions

were normal for the basin. The association of the laminae with an influx of brine into the basin does not preclude that there may also be seasonal relationship although such a relationship has not been identified.

The effect of rain water falling into the basin is negligible for the only effect is to dilute temporarily the surface layer and retard precipitation. The effect of runoff would only be a local change in the composition of the marginal waters. There can be little doubt that some wind blown material was added to the basin.

In the thick (several centimeters) layers of dolomite and anhydrite, pyrite and carbonaceous material are associated with both the upper and lower contacts with the salt. This may represent extermination of some organisms due to the intermingling of the lower dense brine and the added sea water, and final mass extermination with the continued concentration of the brine.

The range of temperature of deposition as determined by a study of inclusions in the halite is between 32 to 48.4° C. The presence of langbeinite offers some substantiating evidence for this mineral is deposited at a minimum temperature of 37° C. This temperature range is undoubtedly a reflection of climatic conditions to a limited extent, although with increased concentration of the brine there is a decrease in the rate of evaporation as an increasing part of the solar energy used to increase the temperature of the brine.

Distinct from the deposits near the center of the basin, the marginal deposits lack the layering of clear and cloudy salt and the laminae are highly irregular, both owing to increased bottom turbulence.

## REFERENCES


ALLING, H. L., 1928, The geology and origin of the Silurian salt of New York state: New York State Mus. Bull., no. 275.

ARNOLD, C. A., 1952, A specimen of Prototaxities from the Kettle Point black shale of Ontario: Palaeont., v. 93 (B), pp. 45–46.

ATKINS, W. R. G., 1924, On the vertical mixing of sea water and its importance for the algal plankton: Marine Biol. Assoc. U. K. Jour., n. s., v. 13, pp. 319–324.

BADGER, W. L. and BAKER, E. M., 1928, Inorganic chemical technology. McGraw-Hill Book Company, Inc., New York, pp. 15–22.

BIRGE, E. A., 1910, An unregarded factor in lake temperature: Wisconsin Acad. Sci. Trans., v. 16, pt. 2, pp. 889–1004.

———, and JUDAY, CHANCEY, 1922, The inland lakes of Wisconsin—the plankton. I, Its quantity and chemical composition: Wis. Geol. and Nat. History Survey, Sci. ser., Bull. 64, no. 13.

BRANSON, E. B., 1915, Origin of thick gypsum and salt deposits: Geol. Soc. America Bull., v. 26, pp. 231–242.

BUCKLEY, H. E., 1951, Crystal growth. John Wiley and Sons, Inc. New York, 571 pp.

BURY, C. R., 1948, The chemistry of saline deposits: Proc. Yorks, Geol. Soc., v. 27, pp. 205–209.

CLARKE, F. W., 1924, The data of geochemistry: U. S. Geol. Survey Bull. 770, 841 pp.

COOK, C. W., 1914, The brine and salt deposits of Michigan: Michigan Geol. and Biol. Survey Pub. 15, Geol. ser. 12, 118 pp.

DELLWIG, L. F., 1953, Hopper crystals of halite in the Salina of Michigan: Am. Mineralogist, v. 38, pp. 730, 731.

DELLWIG, L. F. and BRIGGS, L. I., 1952, Textural relationships in the Salina salt of Michigan (abs.): Geol. Soc. America Bull., v. 63, p. 1242.

DREYER, R. M., GARRELS, R. M., and HOWLAND, A. I., 1949, Liquid inclusions in halite as a guide to geologic thermometry: Am. Mineralogist, v. 34, pp. 26–34.

DUNBAR, C. O., 1949, Historical geology. John Wiley and Sons, Inc., New York. pp. 573

DUNHAM, K. C., 1948, A contribution to the petrology of the Permian evaporite deposits of northeastern England: Proc. Yorks. Geol. Soc., v. 27, pp. 217–227.

FOWLER, A., 1944, A deep bore in the Cleveland Hills: Geol. Mag., v. 81, pp. 193–206, 254–265.

FULDA, Ernst, 1924, Studie über die Entstehung der Kalelagerstattën des deutschen Zechsteins: Zs. deut. geol. Ges., v. 76, Montasber., pp. 7–30.

GRABAU, A. W., 1913, The origin of salt deposits with special reference to the Siluric salt deposits of North America (with discussion): Min. Met. Soc. America Bull. 57, pp. 33–44.
———, 1920, Geology of the nonmetallic deposits other than silicates: v. I, Principles of salt deposition. McGraw Hill Book Company, New York.
GRABAU, A. W. and SHERZER, W. H., 1910, The Monroe formation of southern Michigan and adjoining regions: Michigan Geol. and Biol. Survey Pub. 2, Geol. ser. 1, 435 pp.
GROSSMAN, I. G., 1949, The sodium sulphate deposits of western North Dakota: North Dakota Geol. Survey Rept. Inv., no. 1, 66 pp.
HARVEY, H. W., 1923, Hydrographic features of the water in the neighborhood of Plymouth during the years 1921 and 1922; Marine Biol. Assoc. U. K. Jour., n. s., v. 13, pp. 225–235.
———, 1925, Evaporation and temperature changes in the English Channel: Marine Biol. Assoc. U. K. Jour,. n. s., v. 13, pp. 678–692.
HATCH, F. H., and RASTALL, R. H., 1938, The petrology of the sedimentary rocks, 3rd edition, revised by Maurice Black, Thomas Murby and Co., London, 383 pp.
HILL, A. E., 1937, The transition temperature of gypsum to anhydrite: Am. Chem. Soc. Jour., v. 59, pp. 2242–2244.
HOLLINGWORTH, S. E., 1948, Evaporites: Proc. Yorks. Geol. Soc., v. 27, pp. 192–198.
INGERSON, EARL, 1947, Liquid inclusions in geologic thermometry; Am. Mineralogist, v. 32, pp. 375–388.
JOHNSTON, JOHN and WILLIAMSON, E. D., 1916, The role of inorganic agencies in the deposition of calcium carbonate: Jour. Geology, v. 24, pp. 729–750.
KAUFMANN, D. W. and SLAWSON, C. B., 1950, Ripple marks in rock salt of the Salina formation: Jour. Geol., v. 58, pp. 24–29.
KINDLE, E. M., 1918, Separation of salt from saline water and mud: Geol. Soc. America Bull., v. 29, pp. 471–487.
KRUMBEIN, W. C., 1951, Occurrence and lithologic associations of evaporites in the United States: Jour. Sedimentary Petrology, v. 21, pp. 62–81.
KRUMBEIN, W. C. and GARRELS, R. M., 1952, Origin and classification of chemical sediments in terms of pH and oxidation-reduction potentials: Jour. Geology, v. 60, pp. 1–33.
LANDES, K. K., 1945, Preliminary map no. 40, The Salina and Bass Island rocks in the Michigan basin: U. S. Geol. Survey, Oil and Gas Inv.
LINCK, G., 1937, Bildung des Dolomites und Dolomitisierung: Chemie d. Erde, v. II, pp. 278–286.
LOEWENGART, STEFAN, 1928, Das Tote Meer, seine Entstehung und die Möglichkeiten seiner Ausbeutung: Zs. prakt. Geol., v. 36, pp. 86–89.
LOTZE, FRANZ, 1938, Steinsalz und Kalisalze. Verlag von Gebrüder Borntraeger, Berlin, 936 pp.
LUCAS, P. T., 1954, Environment of Salina salt Deposition: Master's thesis, University of Michigan, Ann Arbor.
MITCHELL, A. E., 1923, Studies on the dolomite system: Chem. Soc. Jour., v. 123, pp. 1055–1065, 1887–1904.
MITCHELL, P. H. and SOLINGER, J. P., 1934, The effect of land drainage upon the excess bases of sea water: Biol. Bull., v. 66, pp. 97–101.
NEWCOMBE, R. B., 1932, Oil and gas fields of Michigan; a discussion of depositional and structural features of the Michigan Basin: Michigan Geol. Survey Div., Pub. 38, Geol. ser. 32, 293 pp.
PEACH, P. A., 1949, Liquid inclusions in geothermometry: Am. Mineralogist, v. 34, pp. 460–461.
PETTIJOHN, F. J., 1949, Sedimentary rocks. Harper and Brothers, New York, 306 pp.
PHALEN, W. C., 1919, Salt resources of the United States: U. S. Geol. Survey Bull. 669, 284 pp.
PHILLIPS, F. C., 1947, Oceanic salt deposits: Quart. Rev., v. 1, pp. 91–111.
PIRTLE, G. W., 1932, Michigan structural basin and its relationship to surrounding areas: Am. Assoc. Petroleum Geologists Bull., v. 16, pp. 145–152.
POSNJAK, E., 1938, The system, $CaSO_4$—$H_2O$: Am. Jour. Sci., 5th ser., v. 35-A, pp. 247–272.
———, 1940, Deposition of calcium sulfate from sea water: Am. Jour. Sci., vol. 238, pp. 559–568.
RANKAMA, KALERVO and SAHAMA, TH. G., 1950, Geochemistry. University of Chicago Press, Chicago, 911 pp.
REVELLE, ROGER, 1934, Physical-chemical factors affecting the solubility of calcium carbonate in sea water: Jour. Sedimentary Petrology, v. 4, pp. 103–110.
RUBEY, W. W., 1951, Geologic history of sea water: Geol. Soc. America Bull., v. 62, pp. 1111–1148.
SHERZER, W. H., 1911, Geological report on Wayne County: Michigan Geol. and Biol. Survey, Pub. 12, Geol. ser. 9, 338 pp.
SHAW, SIR NAPIER, 1928, Manual of meteorology; v. II, Comparative meteorology. Cambridge University Press, London, 445 pp.

SORBY, H. C., 1858, On the microscopical structure of crystals indicating the origin of minerals and rocks: Geol. Soc. London Quart. Jour., v. 14, pp. 450–500.
STEWART, F. H., 1949, The petrology of the evaporites of the Eskdale no. 2. boring, east Yorkshire. Part I. The lower evaporite bed: Mineralog. Mag., v. 28, pp. 621–675.
———, 1951a, The petrology of the evaporites of the Eskdale no. 2 boring,east Yorkshire. Part II. The middle evaporite bed: Mineralog. Mag., v. 29, pp. 445–475.
———, 1951b, The petrology of the evaporites of the Eskdale no. 2 boring, east Yorkshire. Part III. The upper evaporite bed: Mineralog. Mag., v. 29, pp. 557–572.
———, 1953, Early gypsum in the Permian evaporites of northeastern England: Proc. Geol. Assoc., v. 64, pp. 33–39.
TRASK, P. D., 1937, Relation of salinity to the calcium carbonate content of marine sediments: U. S. Geol. Survey Prof. Paper 186-N, pp. 273–299.
———, (Editor), 1939, Recent marine sediments, a symposium, Am. Assoc. Petrol. Geol. Tulsa. 736 pp.
VAN TUYL, F. M., 1916, New points on the origin of dolomite: Am. Jour. Sci., 4th ser., v. 192, pp. 249–259.
VAN'T HOFF, J. H., 1903, Physical chemistry in the service of the sciences: Univ. Dec. Pub., 2nd. Ser., v. 18, Chicago, pp. 97–124.
WALTHER, JOHANNES, 1912, Das Gesetz der Wustenbildung. 2d ed., D. Reimer, Berlin.
WELLS, R. C., 1915, The solubility of calcite in water in contact with the atmosphere, and its variation with temperature: Washington Acad. Sci. Jour., v. 5, pp. 617–622.
WOOD, F. W., 1949, Recent information concerning the evaporites and the pre-Permian floor of southeast Durham: Geol. Soc. London Quart. Jour., v. 105, pp. 327–341.

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# EOLIAN SHAPE-SORTING

RICHARD B. MATTOX
Texas Technological College, Lubbock, Texas

## ABSTRACT

Field and laboratory data obtained in this investigation indicate that eolian shape-sorting is probably of little quantitative importance in coastal dune areas. The conclusion is reached that where such action does occur, the wind tends to select grains of low sphericity values rather than those possessing high sphericity values, as has been stated by some previous investigators.

## INTRODUCTION

Many geologic textbooks and articles contain statements to the effect that sand grains found in eolian deposits generally possess a higher degree of sphericity[1] than do grains found in other types of deposits. The origin of this shape characteristic has usually been attributed to eolian abrasion, especially in the case of many desert dunes which are formed many miles from the source area. However, where dunes are formed close to the source area, as in the case of coastal dunes, the distance of transportation is far too short to allow the development of a high degree of sphericity by the action of eolian abrasion alone. If the sand grains in coastal dune deposits do, in general, have a higher degree of sphericity than the sand grains in the beach deposits from which they are presumed to have been derived, the condition can best be explained by the hypothesis that the wind selects the grains of higher sphericity values from any given deposit. The purpose of this paper is to evaluate this hypothesis and to present field and laboratory data pertaining to it.

## PREVIOUS INVESTIGATIONS

Richardson (1903) stated that, ". . . a round grain will probably run before the wind better than a flat one." The writer interprets this to mean that a more spherical grain, as used in this paper, will roll more easily, or, in other words, can be transported by traction. This idea cannot explain shape-sorting by the wind inasmuch as Bagnold (1937) has shown that most eolian transportation of sand grains occurs by "saltation" (McGee, 1908).

MacCarthy and Huddle (1938) advanced another idea to explain a higher degree of sphericity in sands of coastal dunes than in those of adjacent beach deposits based on the idea that saltation is the principle form of eolian transportation of particles of sand size. On the basis of a series of experiments they concluded that eolian transportation favors sand grains possessing high sphericity values because such grains tend to bounce higher than grains possessing lower sphericity values.[2] They also stated that spherical grains show a stronger tendency to move under the influence of the wind than do grains of lower sphericity values.

A critical examination of this last conclusion leads to disagreement along lines suggested by Free (1911). As a grain approaches the sphericity value of 1.00, the surface area is reduced until at perfect sphericity it has the minimum surface

[1] In this paper the term sphericity is used to denote the shape of a given particle and the sphere is taken as the standard of measurement. True spheres have a value of 1.00; all other shapes have some value less than this.

[2] MacCarthy and Huddle used the term "roundness," but the writer of this paper believes that their use of this term coincides with the meaning of the term "sphericity," as used in this paper.

area for a given mass. Therefore, if two grains of different shapes but of equal mass are subjected to the same wind action, the grain with the lower sphericity value will have the greater tendency to move because of the larger surface area exposed to the wind. Free stated: "The more irregular particles are more easily carried and will be found among material (if regular in shape) that is of smaller linear dimensions." By this hypothesis grains of low sphericity values are selected by the wind and ones of higher sphericity values remain as lag deposits.

## RESULTS OF THE PRESENT INVESTIGATION

*Field Observations.*—In May 1953 the writer spent several days on the Florida coast between Panama City and Pensacola observing the movement of material by the wind. Shell fragments were observed in motion during periods when the wind velocities were not great enough to cause movement of sand grains. It was first thought that this condition existed because the sand was damp but when the shell fragments were placed on the dry sand surface of the dune area, the same action took place. The writer concludes that these fragments moved more readily than the sand because of their greater surface area per unit of mass.

*Comparisons of Beach and Dune Sands.*—Table I shows the results of the shape analyses of beach and dune sands from several locations in the field area. In every case the beach sands show a somewhat higher degree of sphericity than do the dune sands which are located adjacent to them. These results are in direct opposition to those obtained by MacCarthy in a similar study (1935). Several factors may account for the differences noted. One or both investigators could have committed errors in sampling or in the shape analyses of the samples. Also, the short distance of transportation in the field area of this investigation may have been insufficient to allow shape sorting to proceed to a point where its influence was detectable. The writer, however, believes that there is a far more important reason for discrepancies in the results of investigations involving comparisons of characteristics of beach and coastal-dune sands.

TABLE I.—*Comparison of the average sphericities of beach and dune sands*

| Location | Average sphericity | |
|---|---|---|
| | Beach sand | Dune sand |
| 1. Fort Morgan, Alabama | 0.816 | 0.797 |
| 2. Pensacola Beach, Florida | 0.809 | 0.788 |
| 3. 3 Miles east of Fort Walton, Florida | 0.830 | 0.783 |
| 4. Grayton Beach, Florida | 0.826 | 0.783 |
| 5. 1 mile west of Long Beach, Florida | 0.821 | 0.733 |
| 6. Panama City Beach, Florida | 0.828 | 0.760 |
| 7. 3 miles east of Cape San Blas, Florida | 0.808 | 0.751 |

The actions of waves and long-shore currents tend to shift materials along the beaches and thus probably cause the shape characteristics, mineral composition, and size-sorting to be constantly changing at any one geographic location. On the other hand, the dune deposits which border the beaches are, in many coastal regions, relatively stable forms. Therefore, samples of beach sands taken at any one time are probably not representative of the source material of the dunes which are found adjacent to them.

*Experimental Work.*—A large sample of sand was obtained from the Florida coast for use in wind-tunnel experiments on the relationship of wind-transported grains to those of the source material. The floor of the tunnel was covered with sand to a depth of three inches. Samples of the traction and saltation loads were taken in the tunnel during periods when the wind velocities were just sufficient to cause transportation by saltation. The results of the shape analyses of these samples are given in Table II. The saltation load shows a lower average spheric-

ity value than the source material, a condition which the writer regards as suggestive that the wind tends to select grains of lower sphericity values from any given source area.

TABLE II.—*Sphericity analyses of wind-tunnel samples*

| Type | Sphericity | |
|---|---|---|
| | ½–¼ mm | ¼–⅛ mm |
| Source material | 0.811 | 0.791 |
| Traction load | 0.810 | 0.771 |
| Saltation load | 0.768 | 0.775 |

The values given in Tables I and II were obtained using the method proposed by Riley (1941). The values given in Table I were obtained by determining the average sphericity of 200 grains from each of three samples of dune sand and three samples of beach sand at each location. The values given in Table II are based on the shape analysis of 500 grains for each sample.

## OTHER FACTORS OF IMPORTANCE TO THE PROBLEM

*Wind Velocity.*—Regardless of whether the wind selects sand grains of high or low sphericities, shape sorting should occur at the maximum degree when the wind velocity, is at, or slightly in excess of, the threshold velocity. However, in many areas of coastal dunes most of the sand movement takes place during storm periods when the wind velocities are far in excess of those required to initiate or maintain sand movement. The additional fact that in many cases 90 percent or more of the source material consists of sand grains smaller than ½ mm suggests that the sand grains are transported the relatively short distance between the source area and the dune area regardless of their shapes.

*Method of Transportation.*—Shape sorting is dependent upon the method of transportation. Where grains are transported by suspension the more spherical grains, because of their more rapid settling rates, are usually transported shorter distances than grains of equal mass having lower sphericity values; grains with high sphericity values, because they roll more easily, are transported greater distances by traction than are grains with lower sphericity values. Eolian saltation lies somewhere between these two forms of transportation but is here regarded as having more of the properties of suspension than of traction. This line of reasoning leads to the conclusion that if eolian shape-sorting does occur, grains of low sphericity values should be selected from the source areas and would be found in the dune deposits.

This conclusion might be warranted if it were not for the factor of the height of rebound of sand grains in saltation. An increase in the height of rebound results in an increase in the distance of travel because the wind acts upon the grain for a greater period of time. The velocity of the wind increases with an increase in elevation above the surface so that an increase in height of rebound also results in an increase in the average wind velocity acting upon the grain during the period it is above the surface of the ground, and thus an increase in the distance traveled in a single bounce.

MacCarthy and Huddle (1938) advanced the hypothesis that the wind selects the grains of higher sphericity values from a given source area because such grains tend to bounce higher than grains possessing lower sphericity values. The basis for this conclusion was a series of experiments in which sand grains of relatively high sphericity values and grains of relatively low sphericity values were dropped onto a slightly-tilted surface located adjacent to a small barrier. The relative heights of rebound to the two types of grains were checked by determining the number of each type which bounced over the barrier. In two of the experiments the grains were dropped onto a steel plate and in a third this plate was covered with blotting paper.

The writer questions the value of the data obtained in the experiments described above on the basis that the conditions used are not at all like those found in the field. The angle between the path of descent and the surface from which the grains rebounded was, in the experiments, very close to ninety degrees. Sand grains in saltation approach the surface from which they rebound at a very flat angle, usually fifteen degrees or less. Also, the surface upon which the sand grains bounce in their transportation from the shore line to the coastal-dune area is usually composed of other sand grains and is rarely a hard, smooth surface. The two sets of conditions are comparable to a man dribbling a basketball across a smooth floor and then attempting to repeat this act across a surface composed of basketballs. The height and direction of rebound of sand grains in saltation across a sandy surface is determined by the relationship between the surfaces of the residual grains and the transported grains at the point of contact, other things being equal. Therefore, the data obtained by measuring the height of rebound of sand grains by dropping them on a smooth surface are here regarded as of questionable value to the study of eolian shape-sorting.

The results of the wind-tunnel experiments described above would indicate that the factor of shape has little influence on the height of rebound of a grain from a sandy surface in that the saltation load and the source material possessed about the same average sphericity value. Additional experiments in which only the upper portions of the saltation loads were examined indicated that the shape of a grain has little influence on its height of rebound from a sandy surface during transportation by eolian saltation. However, inasmuch as these data were obtained under experimental conditions, the writer plans a field investigation of the problem at an early date.

## SUMMARY

A consideration of the factors discussed above leads to the following tentative conclusions:

1. Shape-sorting by the wind is of little quantitative importance in coastal areas where the distance of transportation between the source area and the dune area is very short.

2. Wind velocities far in excess of the threshold velocity are capable of transporting material of the size grades found in dunes regardless of the shapes of the grains. Therefore, the factor of shape-sorting plays a minor role in determining the shape characteristics of eolian sand deposits in coastal regions subject to winds of relatively high velocities.

3. The comparison of the shape characteristics of adjacent beach and dune deposits is of little value to the study of the action of eolian shape-sorting inasmuch as waves and longshore currents may alter the beach deposits in short periods of time.

4. The nature of eolian saltation is probably more closely related to suspension than traction. Therefore, eolian action should result in the selection of those grains possessing the lower sphericity values in any given source area.

## REFERENCES

BAGNOLD, R. A., 1937, The transport of sand by wind action: Geog. Jour., v. 89, p. 411.

FREE, E.E., 1911, The movement of soil material by the wind: U.S. Dept. Agr. Bur. Soils Bull. no. 68, 36 pp.

MCGEE, W. J., 1908, Outlines of hydrology: Geol. Soc. America, v. 19, p. 199.

MACCARTHY, G. R., 1935, Eolian sands: a comparison: Am. Jour. Sci., v. 30, p. 90.

MACCARTHY, G. R. and HUDDLE, J. W., 1938, Shape-sorting of sand grains by wind action: Am. Jour. Sci., v. 35, pp. 64–73.

RICHARDSON, H., 1903, Sea sand, Yorkshire Philosophical Society Ann. Rpt., 1902, pp. 57–58.

RILEY, N. A., 1941, Projection sphericity: Jour. Sedimentary Petrology, v. 11, pp. 94–97.

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FIGS. 1–5, JUNE, 1955

# COMPOSITE END MEMBERS IN FACIES MAPPING

W. C. KRUMBEIN
Northwestern University, Evanston, Illinois

## ABSTRACT

Most facies maps are designed to show the approach of the stratigraphic section toward one or another of the end members used in the map design. In certain applications of facies maps it is observed that some optimum combination of end members is associated with particular environmental, tectonic, or other conditions, some of which may have practical significance in oil occurrence. A "distance function" based on transformation of trilinear to Cartesian coordinates permits selection of any point within a facies triangle as a center of optimum combination of end members, with contour lines indicating the "facies distance" of any other section from the selected point.

The distance function provides a single system of contours which serve as an evaluation map for more detailed studies of lithologic variations. The relation of the distance function to other contouring systems in facies map design is developed by several illustrations.

## INTRODUCTION

The evolution of contour-type facies maps has shown a tendency toward simplification of method and reduction in the number of separate items contoured on any one map. The use of sandstone, shale, and limestone percentages, for example, requires three sets of superimposed contours. If isopachs are included, the resulting pattern of lines may become very complex. Common practice is to make separate percentage maps for each component.

The use of ratios in facies mapping reduces the three sets of contours to two, and the common practice of coloring selected facies permits relatively easy distinction between facies areas and associated isopachs. The most recent advance in the direction of simplification is Pelto's introduction of classifying and entropy-like functions (1954), which require only a single set of contour lines to summarize the facies relations.

In percentage plotting, each lithology is considered as a separate component, whereas in ratio plotting the mixture of components approaches one or another end member as the ratios themselves approach zero or infinity. In entropy plotting, a series of contour lines indicates approach toward an end member by decrease in the "entropy" of the mixture, i.e., by the progressive dominance of some component toward a vertex of the triangle. By use of a classifying function Pelto also showed that certain composite end members, such as a mixture of 50 percent each of sand and shale, could be distinguished by a decrease in contour values as the particular mixture is approached.

In many facies studies it is observed that some optimum combination of end members is associated with certain tectonic, environmental, or economically important aspects of the stratigraphic unit. An "optimum composite end member mixture" may be defined as some specific combination of end members considered important in a given study. For example, dominant shale with moderate amounts of lime and sand in a basin may grade to dominant limestone with subordinate sand and shale on the shelf. Some particular percentage combination of these rocks may be selected as most indicative of the dividing line between basin and shelf. The selected combination would be an optimum end member mixture for defining a tectonic hinge line. In some back-reef areas a particular combination of evaporites, red shale, and quartzose sand may occur

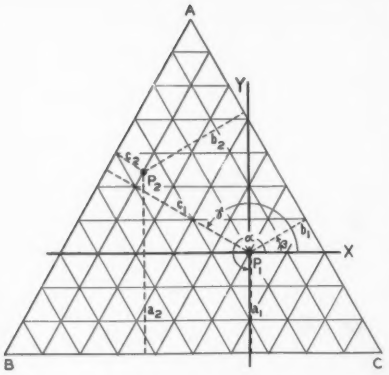



FIG. 1.—Percentage triangle with Cartesian coordinate axes superimposed at point $P_1$.

under certain environmental situations believed to be indicative of near-reef conditions. These proportions may thus define an optimum end member mixture for a specific environment. In some Cretaceous sections oil is known to be associated with a sand-shale ratio of say 0.35. In a regional sense this proportion of sand and shale may form an optimum end member mixture for economic exploration.

Optimum end member mixtures may differ for different areas, different stratigraphic units, or for different end members in the original map design. The selection of optimum mixtures is a matter of geological observation, interpretation, and judgment in a particular study.

It would be desirable to have a method of mapping which permits selection of any desired combination of end members as an optimum end member mixture, and to indicate on a map the degree to which any other combination approaches this optimum. In this way it would be possible to map specific facies trends related to specific tectonic, environmental, or economic objectives in the study. The purpose of this paper is to describe a method for accomplishing this result, based on the geometrical properties of the facies triangle. Several illustrations of the method are also given.

## A SIMPLE DISTANCE FUNCTION FOR EQUILATERAL TRIANGLES

Mertie (1948) reviewed the geometry of equilateral triangles, and his presentation provides a basis for development of a simple "distance function" applicable to facies triangles. One approach is to transform the trilinear coordinates into Cartesian coordinates, and to express the Cartesian coordinates in a conventional distance equation. The writer is indebted to his colleague, Dr. H. A. Slack, for his suggestions in this development.

Figure 1, modified from Mertie (1948), shows an equilateral triangle with end members $A$, $B$, $C$, and point $P_1$ within the triangle at some previously selected "optimum point." The Cartesian coordinate system is centered at the optimum point, with the $X$-axis parallel to the base of the triangle, and the $Y$-axis vertical. This convention makes the $Y$-axis parallel to the trilinear coordinate $a_1$ associated with the $A$-end member, and the $X$-axis is parallel to percentage lines of the A-end member.

The point $P_1$ has trilinear coordinates $a_1$, $b_1$, and $c_1$, measured along lines perpendicular to the edges, and having positive values in the direction of the opposite vertices. In the common convention of plotting points on the triangle, the percentage values associated with the three coordinates are used to locate the point. Thus, $a_1+b_1+c_1=100$.

Point $P_2$ in figure 1, with trilinear coordinates $a_2$, $b_2$, and $c_2$, represents some other combination of end member percentages. To find the distance between $P_2$ and $P_1$, the following transformation equations may be used, adapted from Mertie (1948) to maintain the conventional positive and negative sense on the $X$ and $Y$ axes:

$$x \cos \alpha + y \sin \alpha + a_2 - a_1 = 0 \quad (1)$$

$$x \cos \beta + y \sin \beta + b_2 - b_1 = 0 \quad (2)$$

$$x \cos \gamma + y \sin \gamma + c_2 - c_1 = 0 \quad (3)$$

From the convention followed in setting the $X$ and $Y$ axes in figure 1, it may be seen that the angles involved will always be

$\alpha = 270°$; sin $270° = -1.000$; cos $270° = 0.000$
$\beta = 30°$; sin $30° = +0.500$; cos $30° = +0.866$
$\gamma = 150°$; sin $150° = +0.500$; cos $150° = -0.866$.

Substitution of these values in equations (1) to (3) yields the following expressions:

$$-y+a_2-a_1=0 \quad (4)$$
$$0.866x+0.500y+b_2-b_1=0 \quad (5)$$
$$-0.866x+0.500y+c_2-c_1=0 \quad (6)$$

These equations yield the following values for $x$ and $y$, the corresponding Cartesian coordinates of point $P_2$:

$$y=a_2-a_1 \quad (7)$$
$$x=1.15(b_1-b_2-0.5y) \quad (8)$$
$$x=1.15(c_2-c_1+0.5y) \quad (9)$$

Equations (8) and (9) are equivalent, and either may be used to evaluate $x$. The coefficient 1.15 is the reciprocal of 0.866. Inasmuch as the trilinear coordinates (percentage values) of the optimum point are selected beforehand and the percentages of all other points plotted on the facies triangle are known for a given study, it is a simple matter to find their $x$ and $y$ values. Because of its location at the origin of the new coordinate system, the Cartesian coordinates of point $P_1$ are (0, 0).

The distance function is taken directly from analytic geometry, where the distance $L$ between any point and the origin in a Cartesian coordinate system is

$$L=\sqrt{x^2+y^2}. \quad (10)$$

When plotted on the triangle, fixed values of $L$ form concentric circles centered about $P_1$, as shown in figure 2. A convenient unit of distance is one percent of the length of the perpendicular from any one of the vertices to the center of the opposite edge. Two points are shown in figure 2 to illustrate the method. Point $P_1$, the optimum point, has trilinear coordinates $a_1=30$, $b_1=50$, $c_1=20$;

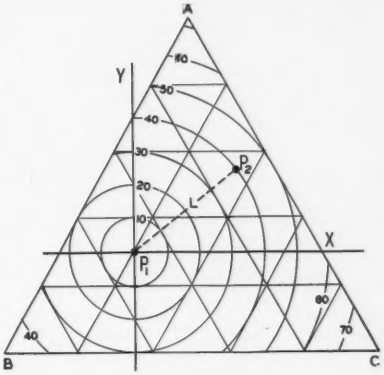



FIG. 2.—Distance between two points on a percentage triangle, as shown by distance contours from point $P_1$.

and point $P_2$ has coordinates $a_2=55$, $b_2=10$, $c_2=35$. From equation (7), $y=25$, and from either equation (8) or (9), $x=1.15(27.5)=31.625$. Thus, point $P_2$ has positive $x$- and $y$-values, as its position with respect to the $X$ and $Y$ axes indicates it should.

From equation (10),

$$L=\sqrt{625+1000.14}=40.3.$$

The value 40.3 represents the distance, in percentage units, between $P_2$ and $P_1$. As shown in figure 2, point $P_2$ lies on the 40-unit circle.

The fact that the distance function plots as a series of concentric percentage circles about the optimum point suggests a simple graphic method for reading the $L$-values directly on any facies triangle. For a given size of triangular graph paper (the writer uses Dietzgen triangular coordinate paper No. 340-TC), a cardboard ruler is made with unit spacing equal to one percent on the triangle. This may be used directly for reading distances between the optimum point and any other point on the triangle.

If $L$ is to be expressed as an actual length, equation (10) is modified to the following where $k$ is the length of the

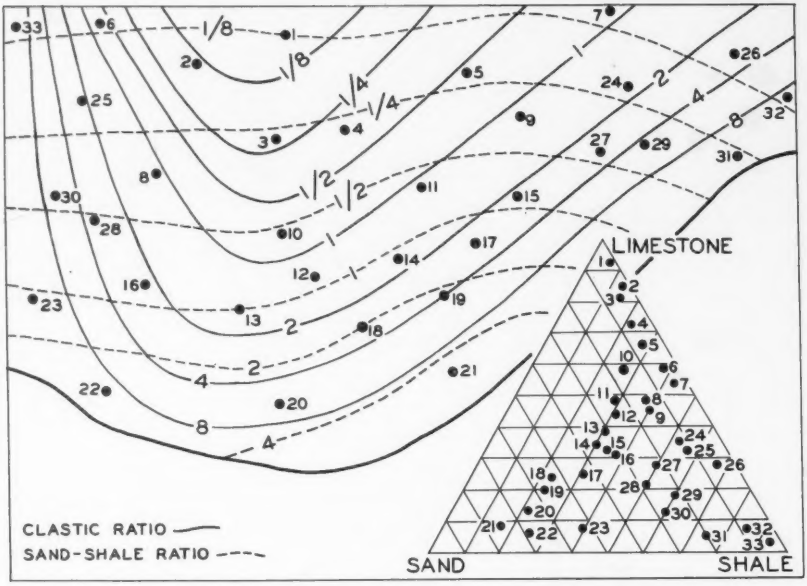



FIG. 3.—Hypothetical facies map based on ratios. Inset triangle shows composition of control points.

perpendicular from a vertex to the opposite edge of the triangle:

$$L=(k/100)\sqrt{x^2+y^2}. \qquad (11)$$

In the Dietzgen paper $k$ is 20.3 cm, and the distance between the two points in figure 2 would be

$$L=(20.3/100)(40.3)=8.18 \text{ cm}.$$

The distance function may be applied to the facies tetrahedron by locating coordinate axes $X$, $Y$, and $Z$ at the optimum point within the tetrahedron, and using as distance function the expression $L=\sqrt{x^2+y^2+z^2}$. The concentric spheres about the optimum point would in this case yield circles or circular arcs on the tetrahedral faces, as the concentric spheres cut the surface of the tetrahedron.

## APPLICATION OF THE DISTANCE FUNCTION TO FACIES MAPS

The distance function may be applied to any facies map having from two to four end members. In two component systems the distance lines cut the ratio lines at equal arithmetic intervals, and in four component systems it is necessary to use a three dimensional distance function. For present purposes a three end member system is used, based on a generalization of some facies conditions that may occur in or near the margins of sedimentary basins.

Figure 3 is a portion of a generalized regional facies map showing clastic ratio lines extending in a bulge southward from a shallow basin center, and the sand-shale ratio lines extending as a broad tongue from the south in the east central part of the map. The resulting pattern of facies lines is roughly parallel in the

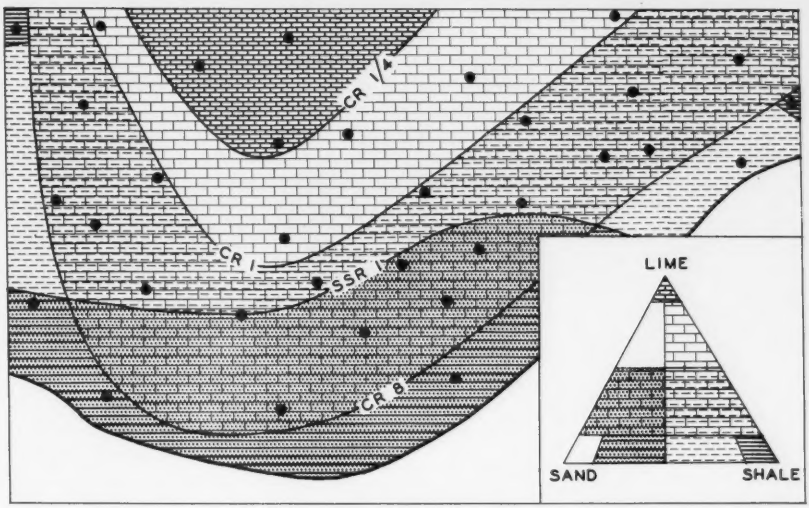



FIG. 4.—Conventional ratio facies map from figure 3.

south central part of the map, with marked discordance in the west and lesser discordance in the east. Maps showing such discordant relations are among the more difficult ones to interpret, especially in economic applications involving the projection of favorable facies trends over the map area. The isopach base is omitted from the illustrations for greater emphasis of the facies lines themselves.

The inset of figure 3 shows the distribution of the control points on a percentage triangle. The points extend along the right edge in the upper part and spread into a wider area of the triangle in the lower part. Figure 4 is a facies map based on conventional ratio limits for later comparison with the distance contours. As this map indicates, an area of limestone end member occurs in the north central part of the map, with shale end members occurring in the extreme northwest and east central parts of the map area. The sand end member is approached in the south central part of the map. Assume for illustration that oil occurs in wells 27, 28, 29, and 30, which are clustered in the lower central part of the triangle of figure 4, and occur in two areas on the map, one in the west and the other in the east. All four points fall in the lime-shale facies. If one were to select this general facies as optimum for oil occurrence, it would imply that a rather wide band sweeping across the map is about equally favorable for oil.

In situations such as this the distance function permits sharper discrimination of that part of the lime-shale facies which

TABLE 1

| Control Point | % Lime | % Sand | % Shale |
|---|---|---|---|
| 27 | 28 | 22 | 50 |
| 28 | 22 | 28 | 50 |
| 29 | 18 | 22 | 60 |
| 30 | 12 | 28 | 60 |
| Total | 80 | 100 | 220 |
| Average (optimum point) | 20 | 25 | 55 |

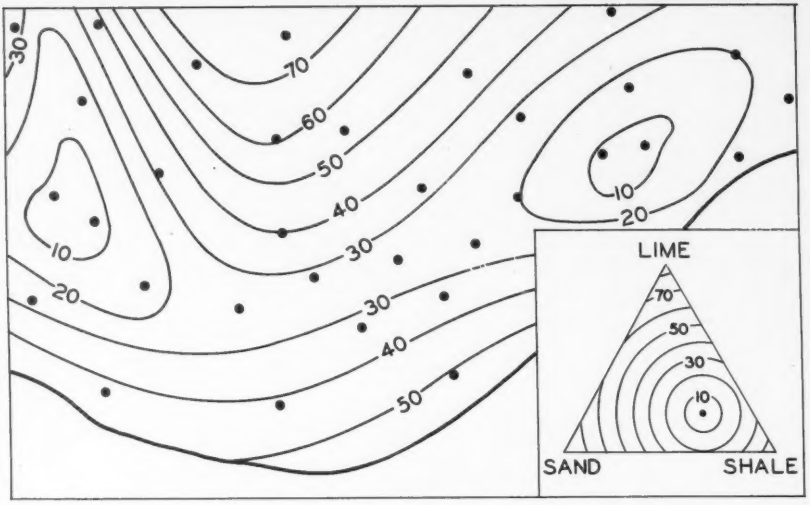



FIG. 5.—Distance function map based on "optimum point" shown in legend triangle. Data from figure 3.

appears to be most closely related to known oil occurrences. An "optimum point" which represents the average of the four oil-producing control points is selected on the triangle, and is used as a center for the coordinate axes in the distance function. The percentage values of the four points are averaged as in table 1, to obtain the percentage (trilinear) coordinates of the optimum point. This point is then plotted on the triangle and is used as a center for measuring the distance of all other points on the triangle. In the present illustration the optimum point has clastic ratio 4.0 and sand-shale ratio 0.45.

The distance values are plotted at the map control points and contoured as indicated in figure 5. The legend for this map is simply a triangle with concentric circles drawn around the optimum point, showing the overlay of the distance function on the percentage triangle. Figure 5 is a "distance function map" which shows two areas of low contour value (indicating little departure from the optimum point) in the east and west parts of the map. These lowest contours enclose the producing areas. A band of value 30 connects the two centers of oil occurrence. North and south of this band the contours increase, indicating increasing departure from the optimum point.

Comparison of figures 4 and 5 shows that the two most favorable facies areas (say within the 20-contour) extend beyond the lime-shale area into the sand-shale pattern on the west and east; and that the band lying between the 30-contours tends in part to straddle the boundary between lime-shale and lime-sand. Thus the contours on the distance function map may extend beyond the optimum facies pattern in some directions, and may lie within them elsewhere.

### RELATION OF DISTANCE FUNCTION TO OTHER CONTOUR SYSTEMS

The distance function depends upon all three trilinear coordinates of any given

control point, and as such it may depart from any one set of percentage or ratio lines. This may be seen by comparing figures 3 and 5. The distance function contours parallel the clastic ratio lines in the north central part of the map, but tend to swing with the sand-shale ratio lines in the south central part. Similar relations would be shown with percentage contours of individual end members.

The relations among the possible ways of setting up contour systems may be seen by referring to the triangle inset in figure 3. The points on the percentage triangle represent the basic data for any facies map in terms of the end members *A*, *B*, and *C* that have been selected for study. In a sense the selection of a particular set of contours is equivalent to superimposing an overlay on the percentage triangle. Such an overlay is a graphic equivalent of a mathematical transformation of the percentage (trilinear) values into ratios, distance-values, "entropy," etc.

In preparing percentage facies maps the triangle provides its own overlay, and the percentages values for each point are used directly on the maps. In ratio plotting a "ratio overlay" is used, which converts the percentage values into clastic ratios, sand-shale ratios, etc., depending upon the end members used. In practice these ratios are computed, but a transparent overlay could be used if desired. Similarly, transformation to single-contour systems such as Pelto's entropy-like function can be accomplished by reading the transformed values through an overlay.

The distance function belongs in the class of single-contour systems, but it has the added property that its overlay may be placed over the percentage triangle in any desired position. If the distance function overlay is superimposed on the percentage triangle in such manner that the origin of the Cartesian system is at the 33.3 percent point for *A*, *B*, and *C*, a map similar to Pelto's entropy-like map is obtained, except that the contour values increase away from the center toward the end members. The physical interpretation of the two maps would be different however, inasmuch as the distance function map expresses geometrical relations only.

The implications of the overlay approach to facies mapping are that maps may be conveniently designed in advance of their actual contouring by plotting the control points on a percentage triangle, and exploring the relations that show up when any of several overlays are put on. In this way the range of percentage values, ratio values, distance values, or entropy-like values may be studied on the triangle in terms of specific objectives of the map study. In addition, means become available for assessing the amount of "information" to be conveyed by the map. If distinction between shaly and sandy limestones is important in a study, some system of contouring may be desirable that makes this distinction explicit.

As Pelto (1954) points out, selection of a given contouring method affects the amount of compositional information conveyed by the map. In general, the more detailed information a map conveys, the more complex the contouring systems tend to become. In actual map contruction there is always the problem of balancing design simplicity against amount of information desired. In the writer's experience more than a single facies map is required to express the full compositional information in a stratigraphic unit. In a set of several such maps the distance function serves as an evaluation map in terms of subject-matter interest in tectonic, environmental, or economic interpretation of the compositional data.

## CONCLUDING REMARKS

The distance function provides a simple geometric method for expressing the similarity or dissimilarity of points on a percentage triangle in terms of distance, regardless of the directional sense of the

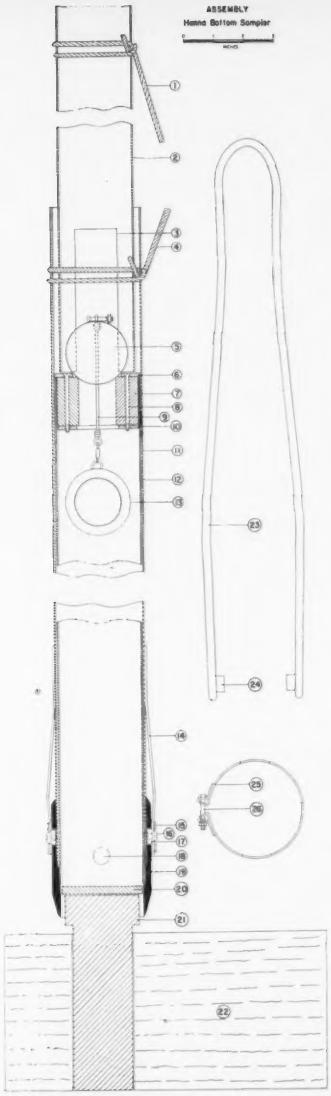
separation. The linear spacing of the concentric circles implies an equal increment of difference for each increment of distance. It is unlikely that facies differences are simple linear functions, inasmuch as lithologic changes apparently tend to follow exponential or power functions over an area.

Pelto's contribution of single contour systems to facies mapping has opened the door to a variety of continuous single-value mapping functions for all points on percentage triangles. The distance function is one such; others based on probability models, especially if they can be related to arbitrarily selected points on the triangle, may also be expected to have direct interpretive significance in evaluation of a wide variety of detailed facies maps.

## REFERENCES

MERTIE, J. B. JR., 1948, Charting five, six, and seven variables on hypertetrahedral faces: Am. Mineralogist, v. 33, pp. 324–336.

PELTO, C. R., 1954, Mapping of multicomponent systems: Jour. Geology, v. 62, pp. 501–511.




The above drawing of the Hanna Coring Tube for soft sediments was inadvertently omitted from the December 1954 issue of the *Journal* where it should have accompanied the paper, "A simple coring tube for soft sediments," by Marcus A. Hanna on pages 263–269. The numbers on the drawing refer to parts and specifications given on pages 267–269 of the December issue.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 2, PP. 124–125
JUNE, 1955

## NOTE

# MINERALOGICAL-PARTICLE SIZE VARIATIONS IN ORIENTED CLAY AGGREGATES

LEONARD G. SCHULTZ
University of Illinois, Urbana, Illinois[1]

A problem often encountered in quantitative clay mineral studies is the possibility of variations in the composition of different size fractions. The usual approach to such a problem is to fractionate the sample and study the various size groups separately. Such a procedure is very time consuming and often unnecessary since every clay does not show appreciable mineralogical variations with particle size.

Considerable time can be saved by first making a rough estimate of variations from a single oriented slide. One method of preparing oriented clay aggregates is to allow the less than two micron particles to settle on a glass slide placed in the bottom of an evaporating dish. The smaller particles settle more slowly than the larger particles and are thus concentrated in the front of the oriented aggregate, whereas the larger particles are concentrated in the back next to the glass slide. X-ray spectrometer traces of the front and back of such a slide permits comparison of the mineralogical composition of the two size fractions. Such a comparison, by itself, may give sufficient information of particle size-composition variations, or it will at least indicate which samples merit further, more detailed work.

Working with Pennsylvanian underclays it was discovered that oriented clay aggregates can often be removed from the glass backing by dropping it several times on a solid surface from a height of six inches to one foot. Other clay aggregates can almost always be pulled from the glass backing with scotch tape. In this way both the front and back of the clay aggregates were investigated. Table 1 gives examples of all types of front-back variations noted. The percentages indicated in the table were determined on the basis of the relative areas of the 001 peaks on the X-ray spectrometer traces (Schultz, 1954). The relative amounts of the illitic and kaolinitic components in the fronts and backs of slides were usually similar for the underclay samples investigated (for example, samples 1 and 2 of table 1). However, some considerable kaolinite-illite variations were noted (other samples of table 1). When present in an underclay sample, a chloritic component was almost always more abundant in the back of the oriented slide (samples 8 and 10 of table 1).

Since the front and back of some sedi-

TABLE 1

| | Sedimented Slide | | | | Slurried Slide | |
|---|---|---|---|---|---|---|
| | Front | | Back | | | |
| | Kaolinite | Chlorite | Kaolinite | Chlorite | Kaolinite | Chlorite |
| 1 | 47% | | 47% | | 50% | |
| 2 | 39 | | 36 | | 36 | |
| 3 | 5 | | 14 | | 6 | |
| 4 | 6 | | 17 | | 6 | |
| 5 | 8 | | 0 | | 2 | |
| 6 | 29 | | 53 | | 45 | |
| 7 | 11 | | 23 | | 18 | |
| 8 | 49 | | 61 | | 54 | |
| 9 | 13 | 0 | 27 | 17 | 22 | 11 |
| 10 | 24 | 4 | 40 | 8 | 29 | 8 |

[1] Present address: U.S. Geological Survey, Washington 25, D.C.

mented slides do vary as shown above, the question arises as to whether the front, the back, or an intermediate composition is most representative of the slide as a whole. The average composition was determined from a spectrometer trace of a slide prepared in a manner which minimized differential settling of various sizes of particles. The dried, less than two micron clay was mixed with a small amount of water and the slurry placed on a glass slide where it was held by surface tension until dry. The small thickness of the slurry on the glass slide prevented any appreiable separation of particle sizes, thus presenting a representative clay surface to the X-ray spectrometer. Such slurried slides, while not always so well oriented as the sedimented slides, were always adequate for quantitative interpretations. Mineral percentages determined from the slurried slides are shown in the last column of table 1. The average composition of the less than two micron fraction of the samples as determined from the slurried slides may be close to that of either the front (samples 3 and 4), the back (samples 5 and 6), or any intermediate composition (samples 7 and 8) of the sedimented clay aggregate. Therefore, it is impossible to be sure what the average composition of a sedimented clay aggregate is unless the front and back are nearly identical.

To summarize, a spectrometer trace of the front side of a sedimented aggregate may give an erroneous impression of the average composition of all the clay in the slide. A slurried clay aggregate gives a much more dependable average composition. A comparison of traces of the front and back of a sedimented slide gives information of mineralogical variations between the coarser and finer particle sizes of a clay aggregate.

## REFERENCE

SCHULTZ, L. G., 1954, The petrology of underclays: unpublished Ph.D. thesis, University of Illinois.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 2, P. 126
JUNE, 1955

# REVIEWS

*How to Know the Minerals and Rocks*, by R. M. Pearl, 1955. pp. 192; figs. 156, Pl. 8; $5\frac{1}{4}\times8\frac{1}{4}$ ins., cloth. McGraw-Hill, New York. Price $3.50.

Geologists are frequently asked to recommend a simple introductory book on minerals and rocks for the novice. This book probably is the best one available for the very beginner. It is less complicated and less comprehensive, for example, than the recent *Field Guide of Rocks and Minerals* (1953) by F. H. Pough, and is better suited for the beginner who does not have much knowledge of the physical sciences. Professor Pearl is both a mineralogist and a good writer who presents his material reasonably accurately in a lively style that is comprehensible to a 12-year old and yet perfectly acceptable to an adult.

The bulk of the book deals with the recognition of 109 common minerals and 22 types of rocks (including "meteorite" and "coal," but not diorite, which seems to be covered under "monzonite"). Attention is quite properly restricted to "sight identification," and the minerals are arranged in the book according to a key of such properties. Although a full page is devoted to the discussion of each mineral, the essential diagnostic features are immediately called to attention by three or four lines of heavy type at the top of each page and by a clever line drawing in which certain characteristic features of the mineral are indicated and labeled.

The principal defect of the book is the same one which plagues others in this class: too many of the color plates of minerals will confuse rather than aid in recognition. One has to conclude that at present there is no economically practical way to reproduce small color pictures adequately in trade books.

D. M. HENDERSON
University of Illinois

*Petrology for Students*, by A. Harker, 8th edition, revised by C. E. Tilley, S. R. Nockolds, and M. Black, 1954. Pp. viii+283; figs. 99; $5\times7\frac{1}{2}$ ins., cloth. Cambridge University Press, Cambridge. Price $3.50.

After nearly 20 years this extremely popular work appears in another edition. Revision this time (about 15 years after Professor Harker's death) is undertaken by three outstanding British petrologists, Tilley, Nockolds, and Black.

No change appears in the scope and organization of the book and revision is primarily one of details. Changes for the most part represent an attempt to improve the selection of rock types described. Some fine examples have been added and more questionable ones deleted.

This concise, lucid, and useful guide to the study of rocks in thin section still retains the excellent reproductions of Professor Harker's beautiful sketches illustrating nearly 200 different rocks under the microscope. It is commendable that in the revision these three men have chosen to distinguish between the terms texture and structure as applied to rocks, a practice not followed, unfortunately, in some of our recent petrological texts.

The appearance of this new edition is certainly worthy of the attention of all petrologists, and readers of this *Journal* will find of particular interest the section dealing with sedimentary rocks.

CARLETON A. CHAPMAN
University of Illinois

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 2, PP. 127–157
JUNE, 1955

# ABSTRACTS OF PAPERS TWENTY-NINTH ANNUAL MEETING SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

The Twenty-ninth Annual Meeting of the Society of Economic Paleontologists and Mineralogists was held in New York City on March 28–31, 1955. Some of the sessions were held jointly with the American Association of Petroleum Geologists and the Society of Exploration Geophysicists.

Society officers for the year April 1955–March 1956 are as follows:

*President:* FRANCIS J. PETTIJOHN, Baltimore, Maryland
*First Past-President:* HANS E. THALMANN, Stanford, California
*Second Past-President:* HAROLD N. FISK, Houston, Texas
*Vice-President:* ROBERT R. SHROCK, Cambridge, Massachusetts
*Secretary-Treasurer:* SAMUEL P. ELLISON, JR., Austin, Texas
*Editor, Journal of Sedimentary Petrology:* JACK L. HOUGH, Urbana, Illinois
*Acting Editor, Journal of Sedimentary Petrology:* RALPH E. GRIM, University of Illinois, Urbana, Illinois
*Editors, Journal of Paleontology:* A. K. MILLER AND W. M. FURNISH, Iowa State University, Iowa City, Iowa

## JOINT SESSION WITH A.A.P.G. AND S.E.G.
March 29, 9:00 A.M.
## PRESIDENTIAL ADDRESS

Presiding for S.E.P.M.: BROOKS F. ELLIS

### PRACTICAL VALUE OF SOME MICROFOSSILS

HANS E. THALMANN

Stanford University, Stanford, California
President, Society of Economic Paleontologists and Mineralogists

At the end of the First World War applied micropaleontology became a new tool for age determinations of sediments and reconstruction of ancient environments in the exploration for oil, with emphasis on the study of fossil Foraminifera, Ostracoda, and other "larger-sized" microfossils. Since the termination of the Second World War much smaller microfossils, hitherto neglected, are increasingly being used for practical purposes in the laboratories of the oil companies, universities, and governmental institutions throughout the world.

Many of these "micro-microfossils" were known to exist in rocks of all ages for more than a hundred years, but their importance and practical value has only recently become evident. In addition to the familiar stereoscopic binocular microscope, modern micropaleontologists now use the biological microscope in order to penetrate behind the secrets of microscopic life in ancient rocks, and the time is not far off when the electron-microscope will reveal the existence of fossil floras and faunas of the smallest imaginable dimensions in continental, brackish-water, and marine sediments of all ages. It looks as if the word "non-fossiliferous" will gradually disappear in stratigraphy or in the dictionary of the micropaleontologists.

Illustrated by lantern slides the future practical value of the diatoms, charophytes, spores and pollen, hystrichosphaerids, peridinids, coccolithophorids, discoasterids, calpionellids, silicoflagellates, and radiolarians is demonstrated. In many of these groups our present knowledge is still scanty but a concentrated effort in cataloguing and evaluating these microfossils under high-power microscopes by academic- as well as practically-inclined micropaleontologists will open up new possibilities for stratigraphic and paleoecologic purposes in the exploration and exploitation of oil.

## MINERALOGY AND SEDIMENTARY PETROLOGY
March 28, 1:30 P.M.

Presiding: R. R. SHROCK, AND RAYMOND SIEVER

### PENNSYLVANIAN LITHOLOGIES AND THEIR SIGNIFICANCE IN NORTHEAST NEVADA*

ROBERT H. DOTT, JR.
Humble Oil & Refining Company,
Eugene, Oregon

Pennsylvanian in north-central Nevada comprises 5,000 feet of cherty limestone, quartz arenite, siltstone, and conglomerate with a major unconformity between middle and upper Pennsylvanian. In east-central Nevada, non-conglomeratic Ely limestone facies (2500–3000 feet) disconformably underlies Wolfcampian with upper Pennsylvanian missing.

Predominant limestone types are calcarenite and calcirudite, particularly crinoidal and fossil hash (microcoquina) varieties, and some oölite. Detrital quartz impurities are characteristic. Brachiopod, fusulinal and other coquinites are common. Coquinoid limestones have sparser, little-damaged fossils. Coralline biostromes are present, but no definite bioherms. Arenites and siltstones with quartz and chert grains grade to arenaceous limestones. Conglomerates contain chert and quartzite fragments.

Fragmented fossils, detrital quartz, oölite and diastems indicate shallow water, frequent agitation, winnowing and redeposition in an unda environment. Orogeny in the eugeosyncline produced lands which shed chert and quartz detritus eastward into the miogeosyncline. Quartz was apparently swept westward from the craton. Local epeirogenic upwarps and platforms within the miogeosyncline subsided less, have significant unconformities, and furnished clastics to adjacent negative areas of more continuous deposition.

Environment of deposition was no different from many epeiric seas of cratonal regions. Greater thickness is the sole significant distinction of these miogeosynclinal sediments.

### SEDIMENTARY ENVIRONMENTS OF COASTAL PLAINS AND THEIR CONTINENTAL SHELVES

W. ARMSTRONG PRICE
Agricultural and Mechanical College
of Texas, College Station, Texas

Basic factors of coastal development are: time, energy, sediment supply, offshore bottom conditions, organisms, climate. Analysis of coastal development involves (1) usual hinterland geological and geomorphic information covering tributary drainage basins, and (2) oceanographic studies of regional wind systems, wave trains, offshore bottoms felt by waves, tidal regime, coastal currents and hydrology of major streams. Feasible numerical evaluation of basic factors is done as time and data permit. A fruitful tool used is a regional geomorphic survey. Thus, principles have been formulated and types and processes, previously incompletely understood or overlooked, described.

Using approach outlined, some 7000 miles of coastal plain on American Atlantic coasts have been typed. During successive high-sea-level periods of the Quaternary, environments have been stable and similar, with major changes in few definitive factors. Thus, each major coastal sector had no more than two major shoreline types. Most variable basic factors have been time (local rejuvenation by vertical or horizontal shoreline movement) and sediment supply (when new transporting agent and sediment supply operated).

A normal coastal plain has been consistently built out in opposition of tectonic deformation. Its contemporary and Quaternary features are dominantly progradational. Glaciated, isostatic rebound and volcanic coastal plain sectors are not considered normal. Depositional plains of off-lapping, coalescing subaerial deltas of low gradient, alluvial-fan type are commonest coastal plain units. With sand excess, strand plains (shoreline terraces) formed by barrier chains ("offshore bars"), with lagoons or coastal marsh belts, develop step-like terrace series. Emerged shelf terraces (surprisingly) are rare, requiring lee coast (low to zero wave energy) free from strand-plain structures and deltaic cover. Known examples are on low, karstic, limestone peninsulas.

Sand carried by longshore drift, powered by breakers, forms beach ridges, barriers and transverse bars in river and inlet mouths, smoothing shorelines and preventing coastal serration by tidal scour. Without such protection, transverse tidal scour produces cross-channeled coasts and funnel-shaped estuaries, maintains transverse patterns of ria coasts and develops tidal-channel networks in marshes, deltas and drowned karst archipelagoes.

* Published with permission of Oak Ridge Institute of Nuclear Studies.

Most new shoreline types described are from neglected, non-scenic coasts with low wave energy, few harbors and low economic development.

## TRIASSIC REEFS OF THE DOLOMITE ALPS, NORTHERN ITALY

NORMAN D. NEWELL
American Museum of Natural History, New York, New York

Triassic reefs of the Dolomite Alps, southern Tyrol, rival the Permian reefs of West Texas in magnitude of development and exposure, hence they rank among the greatest groups of fossil reefs in the world. The principal and only really important work on the Tyrolian reefs was published seventy-five years ago by Mojsisovics who accurately described and interpreted the complex facies relationships, thus paving the way for all subsequent studies of fossil reefs.

For two weeks during the summer of 1954, the writer was able to make an inspection of some of the Tyrolian reefs with the following conclusions: The general facies relationships are remarkably similar to those of the Permian reefs in West Texas. Massive reefs grew horizontally at sea level shedding coarse reef talus into surrounding areas of stagnant (euxinic) facies. Well-bedded back-reef dolomite beds overlie and laterally replace the reefs. The reef-basin boundary is irregular as compared with the margin of the Delaware basin of Texas. Apparently, many of the massifs of the Dolomites are more or less isolated reefs. Further investigation may show that some of these were separate atolls or table reefs.

## RECENT STROMATOLITIC SEDIMENTS FROM SOUTH FLORIDA

ROBERT N. GINSBURG
Marine Laboratory, University of Miami Coral Gables, Florida

In south Florida recent equivalents of many Precambrian and Paleozoic stromatolites occur in the shallow protected marine environment, in the open intertidal zone, and on intermittently flooded mud flats above high water. Millimeter laminae rich in blue-green algae alternate with sediment of the same magnitude. The sediment is particulate $CaCO_3$, mostly bioclastic debris, and abundant carbonate precipitated by algal photosynthesis is not present.

Structures are related to environment:

1. Protected water 1–6 feet. Small discrete spheroid forms whose internal structure resembles common fossil types.
2. Open intertidal zone on rocky shores. Laminated sediments cover tens of square feet, irregularities of rock substratum initiate structures which are preserved by differential sediment binding by algae.
3. Intermittently flooded mud flats above low water. Laminated sediments cover hundreds of square feet; type of laminations and surface structures produced by differential deposition, algal growth, and desiccation; some structures preserved as domes and undulations.

The abundance of micro-folds, micro-unconformities, and animal burrows cross-cutting the laminations in the three types is also environmentally dependent.

Detrital texture and the influence of an adhesive film are the basic criteria for recognizing these types of stromatolites in ancient rocks. The environmental relationships of structures may be useful for paleoecologic interpretations.

## BARRIER ISLAND SEDIMENTARY UNITS ALONG THE GULF COAST*

FRANCIS P. SHEPARD
Scripps Institution of Oceanography, La Jolla, California

The collection and study of several hundred samples from the barrier islands along the central Texas coast and of many samples from other portions of the Gulf coast have led to the establishment of criteria for the recognition of at least four sedimentary environments of deposition within the island margins. These include beaches, dunes, barrier flats, and inlets or channels. The sediments in each are distinctive and can ordinarily be distinguished from the sediments deposited in the bays and on the open shelf.

Using criteria obtained from extensive studies of the Gulf coast environments, the samples from 17 borings into barrier islands have been investigated. It has been found that in most of the borings the sediments are indicative of barrier island environments down to depths of 30 to 50 feet which represent the contact with the weathered clays and oxidized sands indicative of Pleistocene low-sea-level stages of deposition. To date no boring has indicated that barrier islands have grown up from the outer margin of the sand deposition (approximately 30 feet in this area) during a still stand of sea level. It seems more likely that the barrier islands started to develop with the last rise in sea level and built upward keeping pace with the rise. In some places the barrier islands have encroached over the bays

* This investigation was supported by a grant from the American Petroleum Institute Project 51.

but elsewhere the beaches have grown over nearshore Gulf deposits. A surprisingly large proportion of the samples are indicative of the channels and inlets within the islands. Isolated data provided by Humble and Gulf oil companies' offshore drilling operations have indicated that barrier island deposits of considerable thickness lie below relatively thin, open Gulf sediments.

There are some reasons for believing that the barrier islands have grown in part on the top of old Pleistocene barriers so that very considerable thicknesses of sand have developed over more than one cycle. There seems to be no reason why similar sand masses should not have formed during subsidence in earlier periods and particularly during the swinging sea levels of ancient glaciations such as those of "Permo-Carboniferous."

## GRAIN ORIENTATION IN BEACH SANDS: A POSSIBLE MEANS FOR PREDICTING RESERVOIR TREND

R. H. Nanz

Shell Development Company,
Houston, Texas

Long axes of the elongate sand grains on Texas and Florida beach slopes are aligned statistically normal to the beach strike, suggesting that the subsurface trend of beach deposits can be predicted from oriented core samples.

Waves refract as they approach shallow water, their fronts become subparallel to the beach trend and the swash on the beach slope creates currents statistically normal to the beach trend. Other workers have shown that the long axes of experimentally deposited sand grains are subparallel to the direction of water currents.

In the present study, long axis is rigorously defined as the line of minimum moment of inertia of a plane image of the grain. For each sample, long-axis orientations are determined for approximately 300 grains selected on a grid pattern in a polished or thin section and data are plotted in a circular histogram. A mean direction is computed by a least-squares method, spread is estimated by standard deviation, and statistical significance is evaluated by a variance-ratio test. Since the true three-dimensional fabric is planar subparallel to the bedding with a strong lineation, two-dimensional fabric analysis in the bedding plane is sufficient to define the lineation, which is approximately parallel to the current direction.

These findings apply only to beach-slope deposits. They do not necessarily give information on orientation of grains which form the major part of barrier island or shelf deposits.

## ESTIMATION OF RECENT SEDIMENT SIZE PARAMETERS FROM A TRIANGULAR DIAGRAM

William J. Plumley and Donald H. Davis

California Research Corporation,
La Habra, California

Data from 191 size analyses of Recent sediments from several depositional environments were studied to obtain relationships among sediment-size measures and sand-silt-clay composition. A simple analytical procedure exists whereby sediment-size parameters of median, mean, deviation measure, and skewness of Recent sediments may be estimated from a three-component plot of sand, silt, and clay percentages. The three-component analysis is made easily by abbreviated size analysis methods, and the size parameters are obtained graphically from the three-component plot. Conversely, if the median and deviation measure of a sediment sample are known, the composition of the sediment may be obtained in terms of percent sand, silt, and clay. Thus, a one to one correspondence exists between points on the triangular diagram and pairs of median and deviation measure values (excluding the periphery of triangle). The estimation method for obtaining sediment-size parameters will facilitate size analysis of large numbers of Recent sediment samples where semiquantitative data are desired.

## COMPOSITE END MEMBERS IN FACIES MAPPING

W. C. Krumbein

Northwestern University,
Evanston, Illinois

Most facies maps are designed to show the approach of the stratigraphic section toward one or another of the end members used in the map design. In certain applications of facies maps it is observed that some optimum combination of end members is associated with particular environmental, tectonic, or other conditions, some of which may have practical significance in oil occurrence. A "distance function" based on transformation of trilinear to Cartesian coordinates permits selection of any point within a facies triangle as a center of optimum combination of end members, with contour lines indicating the "facies distance" of any other section from the selected point.

The distance function provides a single system of contours which serve as an evaluation map for more detailed studies of lithologic variations. The relation of the distance function to other contouring systems in facies map design is developed by several illustrations.

## ANALYSIS OF SEDIMENTARY FACIES IN POTTSVILLE STRATA OF CENTRAL APPALACHIAN COAL FIELD

E. C. Dapples and R. M. Mitchum

Northwestern University, Evanston, Illinois and Carter Research Laboratory, Tulsa, Oklahoma

Sedimentary facies distinctions are recognized by isolation of subdivisions of Pottsville strata. In lower units quartzose, locally conglomeratic sandstones of wide areal distribution show concentration in marginal part of major sedimentary basin and tend to be distributed in northeast-southwest alignment. Such sandstones gradually disappear as successively higher stratigraphic units are examined, and are replaced by subgraywackes. These become increasingly abundant toward thicker depositional areas and tend to show east-west orientation.

Repetitive cycles of basal, regionally transgressive, quartzose sandstones, overlain by a coal association and shale, characterize lower units. Upper units are typically alternations of subgraywacke sandstones, coal associations, and shale. Shales overlying the coals are distinguished as gray, plant bearing, non-marine varieties; or dark gray, with sideritic concretions, and limestone lenses (marine). The two major shale types are intergradational.

Conditions of deposition are interpreted as follows:

1. Quartzose sandstones represent marine transgressions from northeast to southwest, with sands moved in a southwest direction. Such sandstones are the coalescence of bars along an expanding shoreline.
2. Influx of fine grained, subgraywacke sands and silts from eastern sources to drive shorelines westward, and substitute brackish water conditions leading to coal deposition.
3. Diminution of supply of eastern clastics, and re-advance of the sea over continental deposits as subsidence continued.
4. Gradual suspension of sediment supply from northeast to cut off deposition of quartzose sands during marine invasion.
5. Substitution of dark gray, calcareous shales and thin limestones for deposition of quartzose sandstones. Such occurred when marine conditions were reestablished as the eastern sediment supply dwindled, and continental deposition could not prevail over the continued subsidence.

## THE APPLICATION OF A DISCRIMINANT FUNCTION TO A PROBLEM IN PETROLEUM PETROLOGY

John Rathbone Emery

Carter Oil Company, Tulsa, Oklahoma

From a study of 32 thin sections, 16 cut from the oil-bearing Berea sandstone and 16 from the barren Pocono formation, it has been shown that it is possible, through a linear combination of measured petrographic properties, to differentiate between the Pocono and Berea populations set up in this experiment.

Geologically these formations are similar in age, stratigraphic interval and general lithology and hence the differentiation of oil bearing from barren sediments within a formation will help in the search for petroleum reservoirs within that formation.

A detailed investigation of the 32 thin sections indicated the following generalized differences between the two populations:

1. The average quartz content of the two populations is very similar but the Pocono has a bimodal distribution while the Berea is unimodal. The majority of the Berea samples fall between the extremes shown by the Pocono.
2. The Berea is generally finer grained than the Pocono but its entire distribution falls within the Pocono limits.
3. The Berea is better sorted than the Pocono.
4. There seem to be no important differences between the populations with respect to particle sphericity and orientation. There are differences between individual samples, but when the measurements are combined the populations are not significantly different.
5. The frequency distribution of the packing index of the Pocono samples indicates a strongly bimodal population while the Berea again shows a unimodal form which falls between the modes of the Pocono distribution.
6. The Berea has a higher average porosity than the Pocono.
7. The Berea has a lower average bulk density than the Pocono.

After the evaluation of some of the variables which influence the oil-bearing propensity of a rock, it is possible by use of a discriminant function to describe quantitatively the differences between oil-bearing and barren sediments within a formation. This knowledge may be used as a powerful tool in future petroleum exploration, particularly in the search for so-called "stratigraphic traps."

## APPLICATIONS OF COLLOIDAL MECHANICS IN THE INTERPRETATION OF NATURAL POLYDISPERSE SYSTEMS

J. Robert Moore, III
Harvard University,
Cambridge, Massachusetts

The sedimentological characteristics of extremely fine grained particles found in the present marine environment are analyzed in the light of recent experimental and theoretical research in colloidal mechanics. Data on thermal, electro-kinetic, and gravitational forces affecting dispersion and distribution are presented. Type examples of the so-called red clays and blue muds of the North Atlantic are presented to show that their present distribution patterns are more realistically interpreted by the use of colloidal mechanics applicable to the known current and thermal architecture of North Atlantic waters. Analysis of the variations in the colloidal characteristics at the solid-liquid interface of a discrete clastic particle as it passes through thermal-salinity zones is reviewed.

A statement on the use of colloidal mechanics in the future research in marine sedimentation is given.

## SEDIMENTARY PETROLOGY OF THE CRETACEOUS FORMATIONS OF NORTHERN DELAWARE IN RELATION TO PALEOGEOGRAPHIC PROBLEMS

Johan J. Groot
Delaware Geological Survey,
Newark, Delaware

The purposes of the investigation of the heavy mineral content of the Cretaceous formations of northern Delaware were: (1) to establish a correlation between mineral zones and geologic formations; (2) to discover their area of provenance; (3) to interpret the mineral suites in terms of environmental conditions which must have prevailed in their source area.

Three mineral suites are found in the non-marine Cretaceous formations of northern Delaware. A staurolite suite is correlated with sediments of Patuxent age, a zircon-rutile-tourmaline suite with sediments of Patapsco-Raritan age (undifferentiated) and again a staurolite suite in the Magothy formation. The source area from which these non-marine sediments were derived is thought to be mainly the nearby Piedmont and, to a smaller degree, the adjacent folded Appalachian Mountains.

The marine Upper Cretaceous formations are characterized by an epidote suite. This suite is considered to be the result of mixing sediments from two sources; a source located to the south, and the crystalline rocks of the Piedmont and the Paleozoic sedimentary rocks of the folded Appalachian Mountains to the west.

Observations indicate that Patapsco-Raritan time was a period of intensive weathering in the source area of the non-marine Cretaceous deposits, and it is believed that during that time the Appalachian Mountain system to the west or northwest of Delaware was essentially a peneplain.

## PRELIMINARY STUDY OF MINERALS FROM THE EAST GULF OF MEXICO

Nora Gladwin Fairbank
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

Bottom samples collected by *Atlantis*, research vessel of the Woods Hole Oceanographic Institution, in the eastern Gulf of Mexico, are being studied to find what minerals are present and in approximately what proportions. All samples are surface sediments, and in many the mineral or rock grains are masked in varying degrees by shells and other material of organic origin. A major difficulty is the reduction of abundant organic materials without affecting the minerals. Several different techniques have been tried in order to concentrate the minerals for study. A regular procedure is being worked out in order to arrive at results which will be comparable from one part of the area to another.

As there are over two hundred samples a few have been chosen from each traverse for this study in order to make a reconnaissance of the distribution and zonation with relation to distance from shore and depth of water as well as with reference to continental sources. Both heavy and light minerals have been studied, and a quantitative estimate has been made of mineral distribution both geographically and by species.

## THE STRATIGRAPHIC AND PALEOECOLOGICAL SIGNIFICANCE OF THE SR/CA RATIO IN SEDIMENTS AND FOSSILS

Karl K. Turekian
Lamont Geological Observatory,
Palisades, New York

Strontium is known to substitute significantly for Ca in crystal structure. The extent of the substitution in natural systems such as shells and sediments will be a reflection of the conditions of deposition. This can be demonstrated in several geologic situations such as the depositional environment of the Florena

shale (Permian) and the ecology of contemporary pelagic fauna.

The possibility of Sr abundance data being useful for stratigraphic correlation is strongly limited because of the wide variations observed along the strike in several "typical" formations containing significant amounts of calcium carbonate such as the Harrodsburg limestone (Mississippian) of Indiana.

In a formation where no marked lithologic facies change has been observed over a considerable area, there are significant and consistent variations in the strontium concentrations, which in some cases correlate with the abundance and variation of faunal types.

Variations of Sr concentrations in genera of major faunal groups contemporaneously secreting identical polymorphs of calcium carbonate illustrate the so-called "vital effect."

It is postulated that the "vital effect" can be best explained as a kinetic effect rather than a selectivity on the part of the organism. That is, the speed of shell growth is reflected in the concentration of Sr in the calcium carbonate lattice.

### APPLICATION OF BUSINESS MACHINES AND ELECTRONIC COMPUTERS IN THE REDUCTION OF BOTTOM SEDIMENT DATA

ROBERT E. BURNS AND CHARLES G. PURVES
U. S. Navy Hydrographic Office
Washington 25, D. C.

The rapidly increasing number of bottom sediment samples and cores obtained from various Navy surveys and analyzed at the U. S. Navy Hydrographic Office has led to the development of rapid methods of data reduction. Methods are discussed of utilizing the I.B.M. punched-card system and the I.B.M. Electronic Computor 607 to drastically reduce the amount of hand computation normally required in laboratory analysis of sediments. Proposals are made for future use of these data in testing the various standard sedimentation hypotheses, as well as determining basic correlative relationships that may be present among their analyzed elements.

## RESEARCH COMMITTEE SYMPOSIUM: SEDIMENTARY ASPECTS OF RESTRICTED BASIN DEPOSITION

March 29, 2:00 P.M.

Presiding: E. C. DAPPLES AND BERNHARD KUMMEL

### SYSTEMS OF SEDIMENTATION AND THEIR PHASES

PAUL D. KRYNINE
Pennsylvania State University,
State College, Pennsylvania

The comparative description—and classification—of any item in order to be useful, must operate with certain common denominators, or "polar end members." These are frequently not obvious. Ideally a valid descriptive pole has a definite, almost unique genesis.

In sedimentary basins of deposition, the time honored classification of "environments," from marine sandbars to continental flood plains has hardly ever yielded usable criteria for actual differentiation of a sample. Its categories are para-morphological and not polar. The same, by the way, is true of the current classification of geosynclines, which may be considered as "environments" on a much larger scale.

Systems of sedimentation are made up of depositional loci (so-called "environments") which are "frozen samples" of dynamic genetic conditions which are basically as follows:

1. Ease or difficulty of exit of the load. Basic divisions are (a) "Thoroughfares," such as channels of every type, sandbars, dunes, etc.; (b) "Dead ends," namely interfluves of every breed and hue, melting glaciers, flocculation areas; some "barred basins," mud flows (the very fashionable turbidity currents are not included, since the amount of objective significant quantitative petrographic data presented in support of their volumetric importance so far is nil).

   A further subdivision of "thoroughfares" divides them into those with a linear exit (channels) against those with a lateral exit (dunes).
2. Regimen of current, broken down into: (a) Velocity (theoretically expressed by moment measures for traction and suspension). (b) Time distribution pattern for effective velocity, particularly the "null velocity" of settling. This means in effect ratio of life time of depositional locus occupied by effective velocities. The balance is immaterial.

On the basis of the preceding a tenable and usable description and classification of sedimentary loci or phases becomes possible, essentially because these polar genetic concepts correspond to objective, observable and measurable petrographic criteria, which are also polar. It must be understood that the normal sedimentary system consists of several phases, which frequently cannot exist independently and separately (channel and floodplain). Within this scheme, which is briefly described, a "barred basin" is a chemical dead-end system with several detrital, chemiclastic and fixed crystalline phases, some of them relatively open exit.

All of these phases co-exist (?) in time, and due to tectonic control may follow each other in space, even cyclically (particularly true on a rigid substratum).

The geologic concept of "facies" may refer to passage from one system into another, or to the predominance of a phase within a system. Since this difference is large, it follows that the classical confusion on the subject is also not small.

## CHEMICAL EQUILIBRIA UNDER RESTRICTED MARINE CONDITIONS

Robert M. Garrels
U. S. Geological Survey,
Washington 25, D. C.

Restriction of circulation of marine waters commonly sets up a chain of events with drastic consequences to the sediments deposited. Oxygen is exhausted, organic material is preserved, an entirely new biology is developed, and the solubilities of many inorganic compounds are drastically altered from that of a normal marine environment. In the last decade, much work has been done both on natural restricted environments and on theoretical and experimental systems that have direct application to the natural restricted environments. A summary is given here of several theoretical and laboratory investigations that have significance in environments of restricted circulation. Eh-pH diagrams are provided for iron, sulfur, selenium, lead, zinc, copper, vanadium, uranium, and manganese.

## STARVED BASINS

Hugh N. Frenzel
Midland, Texas

A starved basin is defined as a basin which received a thinner section of deposits than adjoining areas, because the rate of subsidence was materially greater than the rate of deposition. In contrast to ocean basins which have remained starved over long periods of time, intracratonic basins, that show these characteristics, were starved for only portions of their history.

Typical and well known examples are the upper Pennsylvanian Midland basin and the upper Guadalupe Delaware basin. These basins illustrate the range and variation in basins which are called starved. A starved basin condition existed in the Midland basin during upper Pennsylvanian time as shown by the thin black shale section which grades into a thick section of limestone around the margin. The upper part of the Guadalupe series in the Delaware basin is interpreted as a starved basin deposit because these rocks are thinner than the correlative reef and shelf sediments and were deposited 2000 feet below them.

A basin becomes starved when the supply of clastics is restricted by such factors as distance from source, intervening basins or troughs, and the inability because of increasing depth, of normal waves and currents to carry their traction load beyond the basin margin. Also, the depth of the water prevents or inhibits the development of carbonate deposits.

## SEDIMENTARY ENVIRONMENT OF IRON FORMATIONS

Arthur L. Howland and
Harold L. James
Northwestern University, Evanston,
Illinois and U. S. Geological Survey, Menlo Park, California

Sedimentary iron formations, containing from 15 to 40 percent iron, are common in the Precambrian, but occur in a number of other geologic periods and are found on all continents. They are predominantly chemical sediments, intermixed with minor amounts of clastic material and interstratified with shale, sandstone, and limestone. Diagenesis and later replacement seem to have had only a minor role in their formation. A marine origin of most is probable in view of their occurrence in sequences of normal marine characteristics in both Precambrian and younger periods. The iron-bearing minerals—sulfide, carbonate, oxides, and silicates—indicate a wide range in degree of oxidation of the iron at the time of precipitation or during diagenesis. Silica, in the form of chert, is characteristic of some members, particularly in the iron formations of Precambrian age.

Recent studies have emphasized the applicability of modern concepts of stratigraphic analysis to the study of iron formations, even where structural complications are considerable. The concentration of iron and silica indicates conditions of deep weathering for long periods. The dominance of chemical sedimentation may be attributed to low relief of adjoining lands in combination, at least in some cases, with the existence of barred basins that permitted the persistence of special chemical environments and the exclusion of clastic material.

# SYMPOSIUM: SPORES, POLLEN AND OTHER MICROFOSSILS USEFUL IN OIL EXPLORATION

March 30, 9:00 A.M.

Presiding: W. S. HOFFMEISTER, AND ELSO BARGHOORN

## SPORES AND POLLEN—A NEW STRATIGRAPHIC TOOL FOR THE OIL INDUSTRY

RAYMOND D. WOODS
Humble Oil & Refining Company, Houston, Texas

Interest in the use of spores and pollen as a stratigraphic tool has recently been accelerating in the oil industry. It has been demonstrated in a number of areas that the distribution of these fossils is adequate for stratigraphic work and several major companies now have full-time paleobotanists on their research staffs. The science of pollen analysis began with the studies of the Swedish geologist Lennart von Post in 1916. Since then these plant fossils have been used in several parts of the world but primarily for the correlation of coal beds and for interpretations of Quaternary geology. The new emphasis on a wider application of these fossils to general stratigraphic problems is indicated by the special section of *The Micropaleontologist* recently assigned to palynology and by the proposal of a new botanical journal under editorship of Erdtman which will contain a section on the use of spores and pollen as guide fossils for pre-Quaternary geology. Certain of these windblown fossils offer a distinct advantage in permitting correlation of strata deposited under ecologic conditions unfavorable for the distribution of marine or fresh water animals. Certain other forms have been suggested as indicators of depositional environments. In addition, current research on spores and pollen has revealed the distribution of heretofore little known microfossils, particularly the "hystrichs" which are proving to be as useful as plant remains in stratigraphic work.

## MISSISSIPPIAN PLANT SPORES FROM THE HARDINSBURG FORMATION OF ILLINOIS AND KENTUCKY

WILLIAM S. HOFFMEISTER, FRANK L. STAPLIN AND RAYMOND E. MALLOY
Carter Oil Company, Tulsa, Oklahoma

Plant spores from core samples of three wells and five outcrop samples of the Hardinsburg formation of upper Mississippian age from Kentucky and Illinois are described. The spore assemblage consists of 19 genera including 3 proposed as new and 59 species of which 37 are new. The paper includes methods of sample preparation, discussion of literature on Mississippian plant spores, spore assemblages of the Hardinsburg formation, taxonomy, and systematic description of genera and species.

The difference in the technique employed in the maceration of carbonaceous shale from that in the maceration of coal is discussed. Literature on Mississippian spores is meager and vague as the few articles concerning spores of this age refer to coal seams which have not been definitely correlated with type Mississippian sections.

## STRATIGRAPHIC DISTRIBUTION OF PENNSYLVANIAN SPORES*

ROBERT M. KOSANKE
Illinois State Geological Survey, Urbana, Illinois

Many preliminary examinations have been made of the spore and pollen assemblages of Pennsylvanian deposits within the past 10 to 20 years. Some have been entirely concerned with academic descriptions whereas others have been more largely devoted to applied practices related to stratigraphy. It is this latter phase of research with which we are concerned in this paper. Academic paleoecological investigations cannot be separated from stratigraphy.

Straight-laced stratigraphic correlations based entirely on "index fossils" may find many embarrassing pitfalls in the years ahead if the causal factor of plant distribution in time and space are not given proper recognition and study. Interpretation of stratigraphic distribution cannot be made without serious efforts to understand primary plant communities, succession, and dominant communities within a given deposit or those developed throughout Pennsylvanian time.

Published and unpublished data are used in delineating the stratigraphic distribution of genera and species of spores of Pennsylvania deposits. Suggestions are made for harmonizing disjunct stratigraphic ranges, and for the evaluation of interbasinal correlations.

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## STRATIGRAPHIC CORRELATIONS IN PALEOZOIC STRATA

### The Occurrence of Important Plant Spore Species in European, North American, Chinese, Australian and Brazilian Coal Basins

Gerhard Kremp

Pennsylvania State University,
State College, Pennsylvania

The spores of North American Pennsylvanian areas have been well described and illustrated especially by Kosanke, 1950, Cross, 1947, and other authors. Some details of stratigraphic distribution are also given in these publications.

Comparison with the European data shows surprising conformity. Thus 37 species out of 47 figured by Kosanke, 1950, from the upper part of the Tradewater, Illinois, are the same or nearly the same as in the Ruhr Carboniferous—in the Upper Westfal B.R. Potonie and Kremp, (1955, paper in press) studied 535 spore species from Paleozoic strata, and placed them into genera. Of this total they described and figured 185 species from the Ruhr Carboniferous and found that 119 of these species had already been described in Middle European papers by 1945. Twenty-seven other species had been named in North America, four in east and northwest Europe and four in the Kaiping basin (China). These had not previously been recognized in the Ruhr Carboniferous. A large proportion of the species of German origin were already known in North America. In some cases the American authors chose the original names of Ibrahim and Loose, in others they preferred new names. It is believed that the new names would not have been given if in the old papers there had been good photographs instead of drawings which were difficult to compare.

In the last twenty years we have been able to get an approximate picture of the distribution of spores in European Paleozoic strata. The picture gained of the stratigraphic distribution of spores in European Paleozoic strata is nearly the same as that known in the United States.

Especially marked is the similarity of the occurrence of *Densosporites*. It seems to be the same with the spore genus *Lycospora*. Today workers are able not only to correlate coal seams within the same coal basin, but also between different basins. It is to be hoped that eventually our enhanced knowledge can also successfully settle the problems of stratigraphic correlation between North American and European coal basins.

From the dissertation of Imgrund, 1952 it has been shown that the spore distribution in the Kaiping basin (China) is in conformity with those in Europe and Illinois.

The spore flora of Gondwana countries seems to include many genera unknown in the Northern Hemisphere. In the Gondwana flora, three different groups of spores are to be distinguished:

a) Spore genera unknown in the Northern Hemisphere.
b) Spore genera of simple construction, which may be recognized from all ages and all continents.
c) Spore genera also known in the Paleozoic strata of the Northern Hemisphere which, there, are of significant stratigraphic value.

All these spore genera, in the Northern Hemisphere, are first represented in the late Paleozoic, mostly at the beginning of the Permian. The predominant genera of the Carboniferous of the Northern Hemisphere appear to be absent in Gondwana coals. It is particularly striking that the *Densosporites* group which extends from the "Lower Carboniferous" to the end of the "Upper Carboniferous" is not found in Gondwana coals. The same seems to be the case with *Lycospora*, *Florinites* and other important genera. For these reasons it may be possible that at least the "Upper Coal Measures" of Australia are of upper Permian age. The *Glossopteris* flora of the southern continents may have existed in middle Pennsylvanian times in cooler areas. This flora might also be found in northern regions if investigations could be made of coal or clay samples from such cooler areas. More could be said about these aspects if better evidence were available from the southern continents.

## TERTIARY SPORES AND POLLEN RELATED TO PALEOECOLOGY AND STRATIGRAPHY OF CALIFORNIA

W. L. Norem

California Research Corporation,
La Habra, California

When the use of fossil plant spores and pollen was applied to geologic-age dating and stratigraphic correlation, a powerful new tool was introduced in geology. It made possible the correlation and dating of many sedimentary strata that lack other biologic time markers. However, the stratigraphic relationships of any fossil group may not be correctly interpreted unless the ecological relationships of the parent organisms are known. The extensive studies of macroscopic paleobotany in western North America provide a background of botanical and climatic history for the evaluation of the stratigraphic relationships of fossil spores and pollen.

R. W. Chaney, D. I. Axelrod and others have traced the floral changes and migrations

during Tertiary time. The luxuriant floras that developed during the Cretaceous persisted in the Arctic regions until the Eocene and then migrated southward in response to cooling climates. Many genera representative of these Arcto-Tertiary floras reached California during the latter part of the Miocene and persisted there until the Pliocene when rising mountain ranges altered the rainfall pattern.

In California, the Tertiary sediments yield a sequence of fossil pollen and spores extending from tropical and subtropical types in the Eocene, through the Arcto-Tertiary types of the upper Miocene and lower Pliocene into the predominantly coniferous forest types of the upper Pliocene and Pleistocene. In areas of continuous deposition, the changes in the microfloras are related to changes in climate. Abrupt changes occur in the lower and upper Miocene and in the Pliocene. These abrupt changes of microfloras do not necessarily coincide with changes in the aquatic fauna indicating that climatic changes are not always reflected by changes in the aquatic environments.

## MORPHOLOGY AND GEOLOGY OF THE HYSTRICHOSPHAERIDA

L. R. Wilson and W. S. Hoffmeister
University of Massachusetts, Amherst, Massachusetts and Carter Oil Company, Tulsa, Oklahoma

The Hystrichosphaerida constitute a group of organisms whose affinities appear to be with the Protista. They are single-celled structures with a chitinaceous wall which is frequently ornamented with spines, reticulation or extra net-like coverings. Sixteen or possibly seventeen genera are recognized. The geological range of the group extends from the Upper Precambrian to the Recent. Various genera are restricted to certain periods and species are restricted to shorter ranges. Approximately 1000 sandstone, shale and limestone samples have been investigated for hystrichosphaerids and of these nearly 50 percent contained fossils. Eighty-five percent of the fossil bearing rocks were shales and 15 percent shaly limestones. Paleozoic hystrichosphaerids are associated with conodonts, scolecodonts, chitinozoa, brachiopods, corals, and crinoid parts. In Mesozoic and Cenozoic rocks hystrichosphaerids are found associated with Foraminifera, ostracods, spores and pollen. The ecological inferences from rock types and associated organisms is that the older hystrichosphaerids like the Recent were restricted to brackish and marine water. Modern species have been found in shallow to deep water which is brackish or marine, and from subtropical to arctic latitudes.

The hystrichosphaerida because of their small size, diagnostic characters, great abundance and wide geographic distribution meet the requirements for applied micropaleontology.

## MICROPALEONTOLOGY OF HOLOTHURIAN SCLERITES

Don L. Frizzell, and Harriet Exline, (Mrs. Don L. Frizzell)
Missouri School of Mines and Metallurgy, Rolla, Missouri

Fossil holothuians (Echinoderma, Holothuroidea) are known almost exclusively from isolated sclerites, microscopic calcareous particles that support the body of the animal. A unified classification is proposed, following principles of zoological nomenclature, to facilitate the use of these microfossils in micropaleontology, Nine families are defined, with 22 genera and 110 species.

Holothurian sclerites occur questionably in Ordovician rocks, ranging definitely from Devonian to Pleistocene. Except for relatively well known Carboniferous and Jurassic assemblages, knowledge of these microfossils is meager. Vertical and lateral ranges have not been established, although some Paleozoic species are known to be long-ranging and the Mesozoic and Cenozoic species seem to have been shorter lived.

Holothurians are almost exclusively benthonic, crawling on the sea floor, clinging to rocks and seaweed, or burrowing in the substratum. They live in all seas and depths, but almost never in brackish water. Paleoecologically, sclerites indicate warm to cold marine water of normal salinity, from littoral zone to moderate depths, those at greater depth having undergone contemporaneous solution. Reported occurrences are most common from clays, marls, shales and sandy shales, and rare from limestones and the coarser clastics.

# JOINT TECHNICAL SESSION WITH A.A.P.G.

March 30, 1:30 P.M.

# SYMPOSIUM ON THE LATE QUATERNARY GEOLOGY OF MODERN SEDIMENTARY BASINS

Presiding: RUFUS J. Le BLANC and CHALMER J. ROY

## RECENT SEDIMENTATION AS A KEY TO ANCIENT DEPOSITS

PHILIP H. KUENEN
Geologisch Instituut, Gronnigen.
The Netherlands

Examination of an ancient sedimentary basin can provide only an incomplete picture, because it reveals merely the anatomy of a dead body. Physiology must be learned on a living organism, and likewise the geologist must turn to the floor of the present ocean first if he is to gain a full understanding of an oil habitat. On the sea floor processes of transportation, deposition and early stages in consolidation can be investigated along with the accompanying "recent paleogeography." Viewing a sedimentary basin as a succession of sea floors, each with its overlying body of water, will improve interpretation of facies and thus also correlations. Better understanding of relations between environment and the resulting sediment and of gradual development should materially assist in locating likely drilling sites. Now that the more obivous methods for finding oil will soon be nearing the end of their usefulness, it is high time this new approach be fully developed. Up to the present the actualistic method has been sorely neglected in sedimentology as far as shallow waters are concerned. Interest is awakening as the following papers can testify and several other projects have already been launched. Because of the small extent in present times of epi-continental seas the number of suitable areas is somewhat limited and there may not be modern equivalents of all ancient basin types. But an immense amount of work remains to be done until the possibilities offered by the present seas have been adequately exploited.

One of the chief benefits that can come from research on recent sediments is less apparent but none the less real. The participating geologist is trained to think about his basins in terms of processes in addition to his sense of space and time.

## QUATERNARY SEDIMENTATION IN THE GREAT SALT LAKE BASIN

DANIEL J. JONES
University of Utah,
Salt Lake City, Utah

Quaternary sediments in the Great Salt Lake basin are primarily those of Pleistocene Lake Bonneville, and its relict, Great Salt Lake. Subordinate sediment types are fluvial glacial, eolian, and subaerial in origin. The lacustrine facies of each of the stratigraphic units described below has two subfacies: (a) nearshore and/or subaerial gravels, and (b) offshore silts and clays, which in each case, contain distinctive ostracod faunas. Non-lacustrine sediments become increasingly important in the younger formations. The following formational units are recognized, in ascending order, above the volcanics and lake beds of the Tertiary Salt Lake group:

1. *Green Clay series:* 800 to 1000 feet in thickness, composed of (*a*) a piedmont fanglomerate consisting of alluvial fans, and mudflows, grading basinward into (*b*) a series of well-indurated gray-green siltstones and claystones.

—Unconformity—

2. *Alpine formation:* 300 to 400 feet in thickness, composed of the following facies: (*a*) lacustrine sediments whose nearshore gravels are in the form of beaches and embankments, spits, and subaqueous mudflows, grading basinward into thin-bedded silts and clays; (*b*) deltas, well-preserved, built into the lake in embayed areas. Deposits by turbidity currents are common in the Alpine.

—Unconformity—

3. *Provo and younger Pleistocene sediments:* 40 to 80 feet in thickness. These consist of lacustrine and fluvial sediments associated with the later shorelines of the rapidly retreating lake. In addition to shore gravels, deltas, and offshore clays and silts, later sediments include algal reefs, fringes of tufa and tufa-cemented talus-cones. Fluvial sediments consist of terrace gravels and stream channels prograded into the retreating lake. Subaerial deposits of the later Pleistocene include glacial moraines, outwash and alluvial fans.

—Unconformity—

4. *Postglacial and Recent deposits:* 20 to 60 feet in thickness. The following facies are included; (*a*) playa deposits of the Great Salt Lake Desert and marginal areas east of the present lake, with efflorescences of evaporites at the surface, marginal dunes of gypsum and oölites; (*b*) lacustrine deposits of Great Salt Lake, with algal limestones, oölites, and fine-grained clastics; (*c*) fluvial facies of the Jordan River, with flood plain silts and clays, swamp clays and peat, channel sands, and a small delta built into Great Salt Lake.

Sedimentological and paleontological analyses of recently-obtained cores from the southeastern portion of Great Salt Lake indicate that, at a point twenty feet below the present lake bottom, sediments were deposited in fresh-water environment.

Quaternary lake sediments in the Great Salt Lake basin closely resemble marine sedi-

mentary units in shallow relict seas, with similar units such as gravel beaches, spits, hooks, bars, sea cliffs, and turbidity current deposits. Further similarities include fringing and barrier reefs of algal limestones, thin-bedded evaporites, and organic sediments.

## THE BLACK SEA BASIN, ITS POSITION IN THE ALPINE STRUCTURE, AND ITS RICHLY ORGANIC QUATERNARY SEDIMENTS

LEONID P. SMIRNOW
Consultant, Great Neck, L. I., New York

The Black Sea basin forms part of the interior zone of the Alpine mobile belt of southeastern Europe. It is a true sea with a depth of more than 6000 feet. Its formation started in Upper Cretaceous time, and thus is related to other depressions of the Alpine mobile belt.

The block occupied by the Black Sea depression is surrounded by Hercynian and Alpine structures of the Great Caucasus, Small Caucasus, Pontian, and Balkan tectonic units. Characteristics of the Black Sea depression are a deep central portion and very little developed shelf areas.

On the southeast, the Black Sea depression narrows, shallows and merges into the intermountain depression that separates the structure of the Great Caucasus from that of the Small Caucasus. Beyond, to the southeast, the trough merges with the deep depression of the southern Caspian Sea.

It is apparent that in the Upper Cretaceous and Tertiary a very thick series of sediments was deposited in the Black Sea depression. These were possibly geosynclinal sediments of Mediterranean type. During the Pliocene the Black Sea basin had no connection with that of the Mediterranean. From then to the end of the Pliocene the Black Sea was inhabited by a special so-called Pontian fauna, characteristic of brackish waters.

There were frequent changes of salinity in the Bladk Sea basin during Quaternary time. The first increase of salinity was in the Mindel Riss interglacial epoch. This was caused by a connection with the salty Mediterranean waters through the Dardanelles and Bosporus. At that time the Mediterranean fauna reappeared in the Black Sea basin after a long absence. The reason for these sharp changes of salinity in the Black Sea basin is not clear. They could have been created by tectonic movements of the southern (Anatolian) coast. The salinity was also affected by changes of climate in glacial and interglacial epochs, which decreased or increased the inflow of fresh water from the land.

A characteristic of the present Black Sea basin is the poisoning of the water by hydrogen sulfide to almost its full depth of 6000 feet. The waters contain oxygen only to a depth of 450 to 550 feet. The $H_2S$ poisoning of the Black Sea basin started in Wurm time, or a little later, in the so-called Late Euxian basin. The deposits of the marine terraces and of the deeper bottom reflect clearly changes of salinity, oxidation, rate of sedimentation, organic matter accumulation, and other environmental factors.

The recent deposits of the Black Sea are represented by different kinds of muds. Some are very rich in organic matter. Maximal absolute accumulations of the organic matter on the bottom of the Black Sea basin are in its shallow portion, where the water still contains oxygen and where fresh water from rivers flows in. The minimal absolute accumulations of the organic matter are in the zone poisoned by $H_2S$, which are the pelagic areas far from the shores.

Some geologists have thought that the accumulation of the organic matter in the muds of the Black Sea varies primarily with the extent of $H_2S$ poisoning. It is now known that the effect of this poisoning on accumulation of organic matter on the bottom of the Black Sea is exaggerated. As now understood, accumulation of organic matter on the bottom of the Black Sea depends on the whole process of sedimentation—its velocity, the mechanical and chemical composition of the sediments and biological productivity of the basin.

It is hardly possible to compare the Black Sea basin with other recent or any ancient basins, where organic matter was accumulating.

## TWO PERSIAN GULF LAGOONS*

RICHARD A. BRAMKAMP AND RICHARD W. POWERS
Arabian American Oil Company, Saudi Arabia

Preliminary study of two small lagoons at the heads of bays of the Persian Gulf seems to allow easy examination of some general features of carbonate rock and evaporite deposition usually seen only on larger scale. Bars of "beach rock" separate both lagoons from their respective bays, but only one of

* Published by permission of Arabian American Oil Company.

the two lagoons is connected by tidal channel to the adjacent bay.

The lagoon connected with the bay by a tidal channel (26°11′N, 50°10′E), has a salinity of about 55.7 °/₀₀, a nearly uniform general depth of water of 1.3 to 1.5 meters, and floor of lime mud roughly 0.3 to 0.6 meters in thickness. This mud rests on an unconsolidated shelly layer probably the lateral equivalent of the sub-recent "beach rock" of the bar. Along the down-wind shore of the lagoon there is a well-developed depositional shelf of fine pellet calcarenite margined on its offshore side by a sharp change from clean calcarenite to gritty lime mud at a wave base which is at 1.0 meter depth. Lee shores of the lagoon have lime muds up to a steep beach, except where extraneous sand has been blown in.

The other lagoon (26°12′N, 50°02′E) differs in that it receives Gulf water apparently only by wash-over during extreme tides, and shows strong vertical density and temperature layering. In November 1954, 1.0 meter of water with salinity of about 90 °/₀₀ and temperature of 27°C rested on water of salinity of about 200 °/₀₀ and temperature of 34°C. A sedimentary shelf like that of the other lagoon is present on the down-wind side, but along the offshore margin of the shelf ripple-marked platy crystalline gypsum is being deposited. Between the shelf margin and the beach lime mud, sulfide-rich below a thin aerobic surface layer, has been preserved by the binding action of algae.

## RECENT SEDIMENTATION ON THE ORINOCO SHELF

TJEERD VAN ANDEL
Compañía Shell de Venezuela, Maracaibo, Venezuela

The region discussed in the paper covers the continental shelf off the Orinoco delta and around the islands of Trinidad and Tobago and includes the Gulf of Paria. Field and laboratory work were sponsored by the University of Groningen, the Netherlands, and the Royal Dutch/Shell Group and have been carried out by a group of sedimentologists. The investigation has not yet been completed and some of the results are preliminary.

The region includes three major tectonic-physiographic units: the brackish semi-enclosed basin of the Gulf of Paria which has been subsiding since the Pliocene and today collects a major part of the Orinoco sediments; the tectonically stable shelf off the Guayana coast where sedimentation is restricted; and the unstable and topographically irregular shelf north and east of Trinidad where sedimentation is very diversified.

Sediment distribution is controlled by the exposure to the Atlantic swell and by interplay between the northwest-flowing ocean current and the fresh-water outflow from the continent. In the littoral zone along the coast of the mainland estuarine circulation is a dominant factor, which restricts the deposition of modern sands and silts to a narrow zone along the coast. Beyond, in relatively shallow water open to the ocean swell no deposition takes place and sands dating probably from the early Recent transgression occur at the surface. They are post-depositionally glauconitized. Below wave base and in shallow but protected waters uniform Orinoco clays are being deposited irrespective of depth. In areas beyond the reach of terrestrial detritus calcareous muds and oozes form.

The principal sediment source is the Orinoco with the Guayana rivers a moderate second. The part played by the islands and the Paria mountain chain in supplying sediment is negligible.

The paleogeographic implications of the facies distribution are discussed. The lithofacies distribution reflects physical and morphological properties as wave and current distribution and shoreline position. A depth zonation can be based on the microfauna. The presence of islands would be difficult to detect. The relation between regressive and transgressive phases and sand development is discussed.

## PRELUDES TO THE ENTRAPMENT OF ORGANIC MATTER IN THE SEDIMENTS OF LAKE MARACAIBO

ALFRED C. REDFIELD
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

Sedimentation has continued in the Maracaibo basin since the formation of its earliest oil-bearing strata. The present lake is reputed to be one of the most productive waters in the world. Perhaps no more favorable place can be found for examining the conditions presumed to precede the accumulation of organic matter in sedimentary deposits.

The lake appears to have been fresh in the recent past. Sea water gained access to the basin when the rising sea level drowned its approaches to a present depth of 50 feet. Since then marine sediments have greatly reduced the sill depth. Escaping fresh water limits the entrance of sea water which occurs only during three months of the dry season.

The lake water contains about one part

in thirty of sea water, uniformly distributed by an active wind-driven circulation. In the deeper basin, with depths of 100 feet, the salt content is substantially higher. The oxygen content of this "deep water" is reduced and over a large area of bottom is anaerobic.

The fauna of the lake on superficial observation is limited in variety and numbers. Marine forms are restricted to species adapted to life at very low salinities. The significant bulk of organic matter is produced by freshwater species of planktonic algae. These at times produce prominent surface blooms.

The potential fertility of the lake water is revealed by its phosphorous content. The total phosphorus is about 1.4 microgram atoms per liter in the mixed layers above the "deep water." This is more than commonly found in surface waters of the sea. but is less than that of the deep water of the Pacific and Indian oceans. The phosphorus, and presumably other nutrients, are derived from land drainage and are accumulated in the lake by evaporation and by the sinking of organisms into the deep water.

One-third of the phosphorus is present in inorganic form available for plant nutrition. Consequently, growth is not limited by its availability in the photic zone. In the "deep water" the phosphorus content is increased manyfold by the sinking of organisms. The oxygen available is insufficient to oxidize this accumulation, and conditions unusually favorable for the entrapment of organic matter in sediments result.

Sedimentation is active in the lake, particularly in the southwest quarter, where the Catatumbo River is building an extensive delta. Its water discolors the lake for a great distance along the shore. The lake bottom consists of soft blue mud which, in the anaerobic region, is black for several inches below the surface and smells strongly of $H_2S$. The mud is sufficiently unconsolidated to permit a test pile to sink 30 feet under its own weight.

It is concluded that Lake Maracaibo is an unusually favorable place to study the processes which lead to the entrapment and the subsequent transformation of organic matter in sediments.

## OFFSHORE CALIFORNIA BASINS

KENNETH O. EMERY
University of Southern California, Los Angeles, California

The 13 closed basins off southern California are fault blocks having rectangular outlines, steep slopes, and flat floors. They are similar to the now-filled Los Angeles basin and, thus, serve as keys for estimating the environment of deposition of sediments in that oil-rich area. Water below the basin sills is replenished from the open ocean at a sufficiently rapid rate that it is not deficient in oxygen. In contrast, the interstitial water at a depth of a few feet in the sediments is devoid of free oxygen. Oxidation of phytoplankton debris falling through the water column results in loss of about 93 percent. About 50 percent of the organic matter which reaches the bottom is oxidized before it becomes buried to the depth of zero oxygen. Only minor losses occur in the anaerobic zone of the sediment; consequently, most of the organic matter which reaches that zone is preserved when the mud is compacted to shale. After partial conversion into hydrocarbons about 0.15 percent of this deeply buried organic matter is eventually recovered as oil in the Los Angeles basin. Thus, the processes by which phytoplankton becomes converted into petroleum are very inefficient. Comparison of the various basins permits estimation of optimum environments for petroleum accumulation.

## QUATERNARY GEOLOGY OF THE GULF OF MEXICO

MAURICE EWING
Lamont Geological Observatory, Palisades, New York

The basin of the Gulf of Mexico is bounded on all sides by long escarpments which in some cases are more than a mile high. Its floor has a conical shape, with vertex off the Mississippi River. In the two corners farthest from the vertex are found abyssal plains at about 2000 fm depth, on which 1 fm contours can be drawn. A small hill rises about 200 fm above the Sigsbee abyssal plain.

Throughout the basin the top layer of sediment is soft brown globigerina ooze, 25 to 40 cm thick, which is interrupted by a white and a red turbidity current deposit in most of the cores of the Sigsbee abyssal plain. Beneath the brown layer is a dark gray silty lutite with meager microfauna which persists to the bottom of the core in every core in the basin. The change from brown to gray is interpreted as the boundary between Wisconsin and Recent.

During the Wisconsin glaciation the Mississippi River brought the gray layer (unknown thickness, greater than 30 ft) and a turbidity current process distributed it over the entire cone. The small hill in the Sigsbee abyssal plain received none of the gray Wisconsin deposit. If the Mississippi River originated in early Pleistocene, we must infer an extremely high rate of Pleistocene sedimentation.

## GENERAL PALEONTOLOGY AND STRATIGRAPHY

March 31, 9:00 A.M.

Presiding: M. L. THOMPSON AND WALTER YOUNGQUIST

### STRATIGRAPHY OF LATE CRETACEOUS AND EARLY TERTIARY FORMATIONS IN NEW JERSEY

STEVEN K. FOX, JR., AND RICHARD K. OLSSON

Rutgers University, New Brunswick, New Jersey and Princeton University, Princeton, New Jersey

Stratigraphic analysis of late Cretaceous and early Tertiary formations in the Coastal Plain of New Jersey reveals the following:

1. The Upper Cretaceous Navesink, Red Bank, and Tinton are formations with distinct microfaunas indicating time differences.
2. A distinctive new late Cretaceous microfauna from the Red Bank formation contains 84 species. Although many forms are new, a sufficient number indicate correlation with the latest Navarro of the Gulf Coast section. The fauna is easily differentiated from that of the underlying Navesink formation.
3. A completely new microfauna of five species from the Tinton formation differs considerably from that of the Red Bank. Because of the latest Navarro age assigned to the Red Bank, the Tinton may well be post-Navarro and pre-Midway.
4. A new facies microfauna from the lower part of the Hornerstown formation is dwarfed and contains two arenaceous species. Apparently bottom conditions were not favorable for prolific foraminiferal development.
5. A well developed microfauna of 150 species in the uppermost Hornerstown is associated with abundant *Oleneothyris*, *Gryphaea*, and *Polorthus*. Appearance of this fauna suggests more favorable bottom conditions than in the lower Hornerstown. The presence in the fauna of 31 species restricted to the Midway of the Gulf Coast implies strong Paleocene affinities. The occurrence of 57 new species in the Hornerstown reveals the newness of the assemblage and an environmental niche peculiar to New Jersey.
6. A microfauna of 70 species from the basal part of the Vincentown formation contains a mixture of typical Paleocene forms in association with new Eocene elements characteristic of the upper part of the Vincentown. It is assumed that the Paleocene forms have been largely reworked into the lower five feet of the Vincentown where they occur with fragments of *Oleneothyris*, *Gryphaea*, and *Polorthus* and with considerable reworked typical Hornerstown greensand.
7. Comparison of the type Vincentown microfauna with the Hornerstown and basal Vincentown assemblages described above reveals that the type Vincentown is clearly Eocene in age. It contains no diagnostic Paleocene forms.
8. Stratigraphic evidence indicates an unconformity between the Cretaceous and Tertiary formations. The Hornerstown rests successively from northeast to southwest on the Tinton, the Red Bank, and the Navesink. In each case the Hornerstown lies upon a weathered surface and the basal few feet contain fragments of the underlying formation.

### EDWARDS LIMESTONE FOSSILS AS DEPTH INDICATORS*

KEITH YOUNG

University of Texas, Austin, Texas

The Edwards limestone section of Hill, Bosque, and Johnson counties, Texas, contains four distinctive zones of fossils. In ascending order these are: (1) Hexacoralla, Stylinidae; (2) Pelecypoda, Diceratidea and Monpleuridae; (3) Pelecypoda, Capriniade, and (4) Pelecypoda, Radiolitidae and *Chondrodonta*. The shell structure of the pelecypods increases in sturdiness and thickness in ascending order and parallel to the zones of fossils. These zones of fossils and the concurrent patterns of shell structures are interpreted as a depth indicator for the environment of the Edwards limestone sea. The upper surfaces of the Radiolitid and *Chondrodonta* zone are thought to be comparable to the upper surfaces of some modern reef complexes.

### LATE CRETACEOUS CEPHALOPODS FROM SAUDI ARABIA**

W. M. FURNISH AND A. K. MILLER

State University of Iowa, Iowa City, Iowa

* Publication authorized by the Director, Bureau of Economic Geology, The University of Texas.

** Presented with permission of Arabian American Oil Company.

Upper Cretaceous limestones, called the Aruma formation by Steineke and Bramkamp, crop out in an arcuate belt through the interior of the Arabian peninsula. These strata are separated from older Cretaceous sandstones by a prominent unconformity but show little evidence of a missing interval below the overlying Paleocene dolomite. Almost continuous exposures for over 400 miles (between 22 and 28 degrees north latitude) contain a variety of larger foraminifers, corals. echinoids, rudistids and other mollusks including both ammonoids and nautiloids. The ammonite *Sphenodiscus* indicates that the greater portion of these beds are uppermost Cretaceous (Maestrichtian) in age. Some of the associated forms, *Cimomia* and *Deltoidonautilus*, have previously been regarded as characteristic of the early Tertiary.

## THE CARBONIFEROUS GUIDE FOSSIL, *TYLONAUTILUS*, IN AMERICA

A. K. Miller and W. M. Furnish
State University of Iowa, Iowa City, Iowa

In the British Isles, Belgium, and Germany. *Tylonautilus* has long been regarded as an index of the *Eumorphoceras* zone of the lower Namurian, at the base of the Upper Carboniferous. A typical individual was recently sent us from the Fayetteville formation in northeastern Oklahoma. It enabled us to recognize that a small specimen described long ago from the Caney shale of southern Oklahoma is an immature representative of the same genus. Both the Caney and the Fayetteville carry goniatites, including *Eumorphoceras*, like those of the European Namurian.

## CRITERIA FOR THE RECOGNITION OF SPECIES AND SUBSPECIES IN UPPER TRIASSIC METOPOSAURID AMPHIBIANS

Edwin H. Colbert and John Imbrie
The American Museum of Natural History, New York, New York, and Columbia University, New York, New York

The systematics of North American Upper Triassic metoposaurid amphibians is reviewed in the light of three unusually large population samples from Arizona, New Mexico, and Texas, and a fourth from Wyoming. Qualitative examination indicates that seven readily determinable morphologic characters show significant variation: antorbital length, postorbital length, length of skull roof, orbital width, greatest skull width, clavicle width, and clavicle length. Bivariate statistical analysis of logically related pairs of these variates supports qualitative judgment that four morphologically distinct groups can be recognized. Three lines of evidence are employed in an attempt to arrive at the most meaningful taxonomic treatment of these groups. (1) The known biogeography of the essentially contemporaneous Triasics populations. (2) Quantitative estimates of the amount of morphological overlap among the four groups. (3) The amount of morphological overlap in comparable skeletal characteristisc among randomly selected populations of modern mammalian species and subspecies. It is concluded that two subspecies of one species are represented.

Taxonomic concepts and biometrical techniques employed in this study may be readily applied to analogous taxonomic problems involving invertebrate fossils.

## SUBSURFACE GEOLOGY OF COKE COUNTY, TEXAS

Samuel P. Ellison, Jr.
University of Texas, Austin, Texas

An array of facies changes, reef masses, and porosity pinchouts dominate the gentle westward dipping Pennsylvanian and Permian strata. Faulting and folding create complex petroleum reservoir-finding hazards in Cambrian and Lower Ordovician beds below the basal Pennsylvanian angular unconformity along the Bronte uplift in the eastern part of the county. Buried cuestas and isolated hills of the pre-Pennsylvanian topography also account for some reservoirs. Wildcat well density has now reached the point where modern electrical logs become efficient tools for solving lithologic problems and stratigraphic correlations. The trend patterns of facies, reefs, porosity pinchouts, buried topography, faults and folds are applicable to the search for petroleum in adjacent counties on the Eastern Shelf and Concho Arch.

## ENDOTHYROID ZONATION IN THE MISSISSIPPIAN OF THE ROCKY MOUNTAINS

Edward J. Zeller
University of Wisconsin, Madison, Wisconsin

Through the use of endothyroid Foraminifera it has been possible to recognize four widespread faunal zones in the Mississippian rocks of western United States. The faunal succession of the endothyroids and the lateral extent of the four faunal zones were determined by thin-section studies of samples from twelve measured sections distributed along the Cordilleran trough from Arizona to Montana.

The lowermost zone is based upon the presence of a new genus of endothyroid foraminifers and is considered to be Kinderhookian in age. Rocks containing this fauna

are overlain in most areas by those with an especially distinctive new species of *Plectogyra*, most probably Osagean in age. Both of these zones are typically developed in the Madison limestone of Utah, western Wyoming, and Montana.

The two upper endothyroid faunal zones are each characterized by a new species of the genus *Endothyra*. The lower of these zones is Meramecian in age and all of the forms present show close similarity to those in the Salem limestone of the Mississippi Valley area. The species which distinguishes the upper faunal zone is similar to a form in the Ste. Genevieve, but the associated endothyroids seem to have more affinities to the fauna from the type Chesteran. Rocks containing one or both of the upper faunal zones have been found in the Paradise, Escabrosa, and Redwall formations in Arizona and in the Brazer and several thin and unnamed limestones in Utah.

## CLOSE ZONATION OF UPPER CRETACEOUS GLOBIGERINAL SEDIMENTS BY ABUNDANCE RATIOS OF *GLOBOTRUNCANA* SPECIES GROUPS

H. V. Dunnington

Iraq Petroleum Company, Kirkuk, Iraq

Indurated Upper Cretaceous globigerinal limestones have been studied in randomly oriented thin sections providing intersections of large populations of *Globotruncana* species.

The ratio between the numbers of intersected *Globotruncana* individuals showing one peripheral keel and of those showing two or more such keels is almost constant for any stratigraphic horizon, regardless of facies, within northern Iraq.

The ratios vary progressively with age in any vertical sequence, thus providing a rather precise key to stratigraphic position within the age limits of the formations considered.

Detailed observations have been restricted to Maestrichtian-upper Campanian sediments of northern Iraq. It is possible that the values of the ratios may be of world-wide stratigraphic significance, and also that the progressive change may be continuous through sediments of Cenomanian to Maestrichtian age.

## ENDOTHYROID FORAMINIFERAL FAUNAS FROM THE LOWER CARBONIFEROUS OF ENGLAND AND ALGERIA

Doris E. Nodine Zeller

University of Wisconsin, Madison, Wisconsin

An abundant and highly diversified fauna of endothyroid Foraminifera was found in Lower Carboniferous limestones collected in England and Algeria. Comparison of the Lower Carboniferous faunal succession with that of Mississippian rocks in the United States reveals several striking similarities as well as some marked differences.

Certain specimens of *Plectogyra* from the Z zone in England are very similar to a new species in the upper Madison (Osagean?) of Utah, Wyoming, and Montana. The S zone contains a group of planispiral forms which have no known counterpart in American faunas. D zone assemblages from England contain both plectogyroid and planispiral forms which are similar to American Chesteran faunas as well as planispiral species which are totally different. *Parastaffella*, which is not present in Mississippian rocks of America, occurs high in the D zone. The European endothyroid faunas show greater similarity to the Mississippian faunas of the Cordilleran geosyncline than they do to the faunas of the mid-continent region.

Specimens from the upper Viséan at Taghit, Algeria, seem to be conspecific with *Plectogyra phrissa* from the Kinkaid limestone (upper Chesteran) of Illinois. The primitive fusulinid genus *Parastaffella* also occurs in upper Viséan rocks in Algeria.

Associated with the endothyroid faunas are two interesting genera of Foraminifera. *Howchinia bradyana* (Howchin), previously known only from England, has been found in samples from the upper Viséan at Taghit, Algeria. *Archeadiscus karreri* Brady, known to occur in the upper Viséan of Europe, has also been discovered in beds of the same age at Igli, Algeria.

## FORAMINIFERA FROM THE BEAUFORT AND CHUKCHI SEAS

Alfred J. Carsola

U. S. Naval Electronics Laboratory, San Diego, California

Foraminifera populations in 62 sediment samples from the eastern Chukchi and the Beaufort Sea are generally small.

Planktonic Foraminifera are generally rare, but in a few samples they are the dominant forms found in the bottom sediments. The principal planktonic species is *Globigerina pachyderma* Ehrenberg.

The benthonic assemblage in the Chukchi Sea differs somewhat from that in the Beaufort Sea. probably as a consequence of the temperature barrier in the surface waters which separates these two seas. A depth zonation of benthonic faunas exists, with three zones being delineated. One is shallower than 65 m, one lies between 65 and 450 m, and a third zone is found in water deeper than 450 m. Indications are that these zones are largely dependent on sea surface temperature, which affects ice cover and thus organic production,

and ultimately affects the ecologic conditions obtaining near and on the sea floor.

## ANCESTORS OF THE QUAHOG

H. B. STENZEL

University of Houston, Houston, Texas

The common living hard-shell clam of the North American east coast, *Mercenaria mercenaria* (Linne, 1758), commonly known by its Algonquian Indian name quahog, is the type species of *Mercenaria* Schumacher, 1817. The only other living congener is *M. campechiensis* (Gmelin, 1791) from the south coast. The genus is abundantly represented by several species and many individuals in the Oligocene, Miocene, and Pliocene deposits of the Gulf and Atlantic Coastal Plains. Because it is not found outside this region, it is evidently a provincial stock unable to spread. Hence its ancestors must be found in the Coastal Plains.

*Mercenaria* is the only Oligocene to Recent genus of the *Veneridae* that has rugose nymphs; it is also one of the few having a thick shell with crenulate margins and a peculiar radiating shell-wall structure created by the growing crenulations. Below the Oligocene, the only genus having such features is *Rhabdopitaria* K. Van W. Palmer, 1927, with the type species *R. astartoides* (Gardner, 1923) from the middle Eocene of Texas. This middle to upper Eocene genus is provincial in the Gulf Coastal Plain and ancestral to *Mercenaria*. Rapid evolution at the Eocene/Oligocene turn is responsible for the loss of the left anterior lateral hinge tooth and its corresponding socket in the right valve, present in *Rhabdopitaria* and lacking in *Mercenaria*, and the subsequent shifts of some of the hinge teeth.

Present classification of the family, based on the dentition, separates the two genera into different subfamilies, unjustifiably so. Dentition is a progressive feature in this family and not so reliable for classification as are the conservative nymphal rugae and crenulate shell margins.

## SALT DOMES STRATIGRAPHY—LOWER GULF COAST

SHEPARD W. LOWMAN

Rensselaer Polytechnic Institute, Troy, New York

The stratigraphy of salt domes is divisible into (a) regional stratigraphic setting of the domes and (b) characteristic effects produced by domes on local stratigraphy. Under the regional category an attempt is made to distinguish those features which are essential to salt dome formation. In the local class the effects produced by shallow and deep-seated domes are considered. Discussion is limited to the lower Gulf Coast of Texas and Louisiana.

## FORAMINIFERA OF THE AUSTIN GROUP IN NORTHEAST TEXAS*

CHARLES L. MCNULTY, JR.

Continental Oil Company, Roswell, New Mexico

This research involves the arcuate belt of Austin outcrop extending through Dallas, Collin, Grayson, and Fannin counties of northeast Texas. The area is located on the northwest flank of the East Texas basin, where the strata dip gently south and east. Here the Austin group includes a calcareous facies, extending from Dallas County northward to Grayson County, and an argillaceous facies, extending from Fannin County eastward. Correlation of these facies has been a subject of controversy.

Although 143 foraminiferal species have been reported from the Austin, the low density and vague stratigraphic location of sample localities justify a systematic examination of its microfauna. Such examination was the primary objective of this study. In addition, the research anticipated some basis for zonation of the Austin group and clarification of the relations of calcareous and argillaceous facies.

Approximately 300 samples were collected and their stratigraphic position determined accurately by surveying.

The foraminiferal content of the samples includes 148 species, 11 of which are new, 8 possibly new, and 38 hitherto unreported from the Austin of Texas.

Nineteen species overwhelmingly dominate the faunal population and, in varying proportions, constitute from 75 to 90 percent of a given faunule population. Vertical variation in relative abundance of the 19 species reveals a gradual change from pelagic to benthonic types during the time of Austin deposition.

Fourteen species may be considered diagnostic of Austin strata, *Citharina texana* (Cushman) being the most useful by reason of its persistence.

The obvious dissimilarity of Austin-Eagle Ford faunas and the striking similarity of Austin-Taylor faunas, suggest that the Upper Cretaceous of Texas may be subdivided into two series at the Eagle Ford-Austin contact.

The fauna of the Austin group is divisible into a lower and upper fauna at the zone of *Exogyra ponderosa* Roemer (?), which appears to mark a hiatus. The lower fauna is named the normal Austin fauna and is characteristic of all the calcareous facies except its uppermost strata. The upper fauna is named the Gober fauna and is characteristic of all the argillaceous facies except its lowermost

* Abstract of dissertation submitted to the Graduate School, University of Oklahoma, in partial fulfillment of the requirements for the degree of Doctor of Philosophy, 1955.

strata. Each fauna defines a faunal zone that can be traced along strike.

Along strike the unconformity of the *Exogyra ponderosa* Roemer (?) zone gradually truncates strata of the normal Austin faunal zone, causing it to thin northward. Conversely the Gober faunal zone, which is thickest in northern Fannin County, thins southward.

Uppermost strata of the Gober faunal zone change facies southward from chalk to marl and have been included hitherto in the Taylor group in Collin and Dallas counties. It is recommended that these lowermost "Taylor" strata, which have been demonstrated to be a mappable unit, be removed from the Taylor group and assigned to the Austin group.

### THE MEGAFAUNA OF THE FLORENA SHALE OF SOUTHERN KANSAS

BRUCE H. WALKER

Richmond Petroleum Company, Bogotá, Colombia

The megafauna of the Permian Wolfcampian Florena shale of southern Kansas is described. Twenty-two genera and 30 species are recognized. The 22 genera in the collection are represented by one coral, eight brachiopods, one ammonoid, seven pelecypods, four gastropods, and one trilobite. All of the genera, with the exception of the ammonoid, are present in the Pennsylvania system. This is the lowest reported occurrence of *Paraceltites*.

The most noteworthy feature of the fauna is its dominant Pennsylvanian aspect. Twenty-one of the genera and 20 of the species are found in the Florena and in Pennsylvanian rocks below. The faunal similarity indicates a very close relationship in time between the two systems and testifies a very close relationship in time between the two systems and testifies to their similarity of ecologic conditions and to a lack of any great time break between the Pennsylvanian and Permian systems in this region. The Florena fauna compares quite closely to those of other Wolfcampian horizons of approximately the same age in Texas, New Mexico, Arizona and Utah. The presence in the Leonardian series of 15 of the 22 genera found in the Florena shale testifies to the long range of those genera.

## JOINT TECHNICAL SESSION WITH A.A.P.G.

March 31, 1:30 P.M.

## HABITAT OF OIL IN THE DEPOSITION BASIN

Presiding: HAROLD W. HOOTS, AND MARSHALL KAY

### THE EASTERN INTERIOR (ILLINOIS) BASIN AS A HABITAT FOR OIL

ALFRED H. BELL AND DAVID H. SWANN

Illinois Geological Survey, Urbana, Illinois

An oval 12,000-foot, 90,000-cubic-mile Paleozoic basin underlies 55,000 square miles of central and southern Illinois, southwestern Indiana, and western Kentucky. Its eastern and northern flanks were defined in late Cambrian time, its northeastern by Middle Ordovician, its western during Middle Ordovician, and its southern after Pennsylvanian.

With 63,000 wells and 27,000 dry holes, this basin has produced 2 billion barrels of oil in 50 years and is maintaining 0.8 billion barrels proved reserves despite annual withdrawal of 85 million barrels. Ultimately the upper half of the stratigraphic column will probably yield 3.5 to 4 billion barrels.

The lower half of the basin has not produced oil and is still virtually unknown. Except at the margin, only 11 wells with 6000 feet total penetration below St. Peter sandstone reach the 45,000 ± cubic miles of Upper Cambrian and Lower Ordovician rocks. Dolomite dominates this section around the margin and sandstone is abundant near the base and along the north edge. Limestone and shale are uncommon.

Oil is related to the tops of three major carbonate sequences in the upper half of the column, each a few hundred to two thousand feet thick, and underlying an essentially clastic sequence. Most oil is either in the top 100 to 200 feet of the carbonate sections, or in sandstones in the lower part of the clastic sections.

One-half of one percent of the basin's oil occurs on the west slope in crinoidal limestone with intergranular porosity, high in the Middle Ordovician carbonate sequence.

Six percent has come from Lower Silurian to Middle Devonian dolomite, limestone, and sandstone reservoirs in reefs, pinchouts, drapes, and normal structures, having in common only their position near the top of Silurian-Devonian carbonates. Early Middle Devonian dolomite is most productive. Middle Silurian reefs peripheral to a thinned central starved basin provide a few reservoirs and more cores over which later reservoirs are draped in compactional domes.

Over three-fourths of the basin's oil is Mississippian. Less than one percent is from reservoirs beneath or well within the major

lower Mississippian limestone sequence. About 23 percent is from the top 150 feet or so of the limestone, nearly all in oölite. Where the limestone was eroded on the LaSalle anticlinal belt in the northeastern part of the basin, successively older lower Mississippian formations serve as reservoirs as each reaches the top 150 feet.

About 54 percent of the oil comes from upper Mississippian (Chester) sandstones. The prolific formations are toward the bottom of the sequence. In most formations, oil is more abundant in scattered lenses than where the formation is a blanket sandstone. Middle and upper Chester sandstones are more prolific on the east side of the basin and in faulted areas.

Only minor amounts of oil appear indigenous to the Pennsylvanian, though it yielded 15 percent of the basin's total, largely along the LaSalle belt. Most Pennsylvanian oil probably migrated across the unconformity from immediately underlying Mississippian rocks; some migrated upward along faults.

## OIL IN THE MICHIGAN BASIN

GEORGE V. COHEE, AND KENNETH K. LANDES
U. S. Geological Survey, Washington, D. C. and University of Michigan, Ann Arbor, Michigan

The Michigan structural basin, which includes the Southern Peninsula and the eastern part of the Northern Peninsula of Michigan, parts of eastern Wisconsin, northeastern Illinois, northern Indiana, northwestern Ohio, and southwestern Ontario, was one of the first areas in the country to be explored for oil and gas. Interest spread to eastern Michigan following the discovery of oil near Petrolia in Ontario soon after the Drake well was drilled. Production at shallow depths was found along the eastern, southern, and western margins of the basin during the early exploration, but reservoirs in the deeper part of the basin have been discovered only in the last 26 years.

Oil and gas occur in reservoirs on anticlinal folds that are the result of uplift and deformation during late Paleozoic time. In the central basin area, northwest-southwest structural trends predominate, but in southwestern Michigan there appears to be no dominant structural trend. The oil and gas reservoirs are porous zones in limestone and dolomite of Middle Ordovician, Middle and late Silurian, and Middle Devonian age; and sandstones of Middle Devonian and early Mississippian age. A small amount of natural gas has been produced from sandstone of early Pennsylvanian age. The porosity, permeability, and salt water content of the limestone and dolomite reservoirs vary considerably in different producing areas and some of the producing zones are very lenticular.

Approximately 270 oil fields and more than 100 gas fields have been discovered in the Michigan basin. The size of the fields ranges from a few acres to more than 6000 acres productive in oil and 11,000 acres productive in gas. The depth at which commercial production has been found to date ranges from 110 feet in an old field in northern Essex County, Ontario, south of Lake St. Clair, to more than 5000 feet in the central part of the basin. The largest fields are in the central basin area.

It is estimated that more than 95 percent of the oil produced has been from limestone and dolomite of Middle Devonian age. Most of the gas has been produced from sandstone of early Mississippian age; dolomites of Middle and late Silurian age, however, have yielded large quantities of gas in southwestern Ontario and southeastern Michigan. Approximately 400 million barrels of oil and 330 billion cubic feet of gas have been produced from fields in the Michigan basin excluding the Lima-Indiana Trenton field at the southern margin of the basin, which has produced about half a billion barrels of oil and a large quantity of gas.

## THE EMPLACEMENT OF OIL AND GAS IN THE APPALACHIAN BASIN

HERBERT P. WOODWARD
Rutgers University, Newark, New Jersey

Cradle of the American oil industry, the Appalachian basin originated as a stratigraphic trough whose present deep-buried floor was the ancient Precambrian erosion surface first covered by Cambrian seas. It now holds an intricate series of marine and continental sediments whose deposition followed a fairly constant pattern, with primary source at the east, medial thickening, and an outer, western, zone of facies change and shoaling conditions along the east flank of the Cincinnati arch that formed a hinge in the subsidence following each formational deposition. The same country is now a structural trough shaped during orogenesis that finally crumpled the former source area into the familiar Appalachian highlands, and whose foreland or shallow folds were thrown far west even of the center of the trough. Details of local orogenic history show at least two early stages of folding overridden by the final fold pattern with actual or incipient domes at various points of intersection.

The Appalachian sedimentary trough was also a supply basin for petroleum hydrocarbons that moved mainly upward and outward to become concentrated in border zones having suitable reservoir qualities. Such zones have a present basinal position that generally

parallels the west margin of the individual horizon, wherein emplacement of oil and gas was controlled primarily by favorable shoreline porosity and secondarily by fold patterns, with major impounding at the intersection of early and late folds. Subsequent differential sorting of the fluid systems of connected reservoirs was a result of gravitational flushing with concentration ultimately determined by relative buoyancy and local reservoir elevation.

Other specific Appalachian entrapment occurs along linear carrier beds, in sedimentary wedgeouts, in fracture systems, in deep relic reservoirs, and in uncompromised islands of favorable porosity within regions otherwise unfavorable. The possibility of locating additional reservoir traps in the deep central basin, along the basement floor, or below unconformable surfaces, is favorably regarded. Special attention should be paid to the northeast end of the Appalachian basin, particularly east of the Adirondack arch, out of which no production has yet been found, but which has been imperfectly tested so far.

Similarities are discussed between such blanket-sand deposits as the Tuscarora-Clinton, Oriskany, and Berea horizons; the shallow younger producing sands are treated as another genre; and the possible future development of still other horizons is anticipated.

Finally, with this familiar basin as a type, certain basic principles are adduced toward a general hypothesis of the basinal emplacement of oil and gas.

## THE LOS ANGELES BASIN

WILLIAM F. BARBAT
Standard Oil Company of California, San Francisco, California

Los Angeles basin was formed by crustal movements in mid-Miocene time. Following a rapid marine invasion, the basin received a series of alternating fine-grained (silt-clay) and coarse-grained (sand) sediments, which were deposited in deep water. By mid-Pliocene time the basin started to fill up and the sea was gradually expelled. An estimated maximum of 20,000 feet of beds was deposited in this cycle. The basin suffered only very mild deformation until mid-Pleistocene time when a central syncline, bordered by marginal anticlines, was formed. The orogeny produced only moderate relief and there has been little subsequent erosion of the sediments. With minor exceptions the oil production is related to preregressive sediments and to large closed structural traps formed around the periphery of the basin.

Oil was discovered in 1880 and production to January 1, 1954, has been approximately 4.2 billion barrels of oil from 44 oil fields covering 39,583 acres, or 61.8 square miles. This represents an average recovery to date of 106,032 barrels per acre. However, the Long Beach field, with the most prolific production to that date, has averaged 499,175 barrels per acre.

The drainage area of the Los Angeles basin is estimated to be 850 square miles, which contains an estimated 2000 cubic miles of sediment. There have been 1453 new-field wildcat wells drilled to January 1, 1954, or at an average density of 1.7 wells per square mile. Wildcat density, of course, has been much greater through the more prospective portions of the basin. This, as well as seriously competing uses for the land, may lessen future exploration.

The possible extension of the basin under the waters of the Pacific Ocean may yield additional new oil, but there are serious technological, economic, and political handicaps to overcome before this may become a reality.

The high productivity of this basin for its size may be governed by these factors:

1. Ample deposition of organic material.
2. Adequate protection from chemical and biological destruction.
3. Ample load compression, particularly in the center of the basin, to squeeze entrapped fluids from the fine-grained rocks.
4. Ample interfingering of carrier and reservoir sands with the fine-grained rocks.
5. Available traps of considerable size near the margins of the basin to remove hydrocarbons from the fluids before they were expelled.
6. Relative geological youth of the basin, absence of a long-standing load of superjacent rock, and a single moderate orogeny, resulting in little post-depositional alteration of the sediments.
7. Absence of large-scale uplift and major erosion with consequent preservation of reservoir pressures.
8. Intense exploration and development.

## OIL IN THE SAN JOAQUIN VALLEY, CALIFORNIA

RUSSELL R. SIMONSON
The Ohio Oil Company, Los Angeles, California

More than six and one-half billion barrels of oil have been discovered in the San Joaquin Valley. Approximatly four and one-quarter billion barrels have been produced and there is a reserve of two and one-quarter billion barrels. San Joaquin Valley oil fields account for 42 percent of the annual production and contain 45 percent of the reserves of the state.

Ninety percent of the oil produced to date has come from rocks which are Miocene or younger in age. Non-marine sediments, largely of Miocene or later age, have accounted for one and one-half billion barrels of oil or 35 percent of the total production of the valley. Oligocene and Eocene reservoirs are assuming importance as deeper drilling is done and new areas are explored. The pre-Tertiary sediments have accounted for less than one percent of the oil produced. However, Cretaceous rocks are now being actively prospected.

The San Joaquin Valley is a synclinorium some 250 miles long and 50 to 60 miles wide lying between the Sierra Nevada Mountains to the east and the Coast Ranges to the west The maximum depth to the basement is estimated to be in excess of 35,000 feet with the thickest sedimentary section being on the western side of the valley. Oil production is confined mainly to the southern portion which contains a thick section of organic Tertiary sediments.

The San Joaquin Valley does not lend itself well to the basin analysis suggested by authors. The geosynclinal trough is present as is the Sierra Nevada foreland to the east. Numerous faults of minor displacement along the east side of the valley might be termed a "hingebelt" but they interrupt the regional dip in only a minor way.

The San Andreas and other faults of large lateral displacement have probably altered or removed the "geanticlinal welt" if it ever existed on the west side of the valley. Furthermore, the western boundary of the valley has been transgressed many times by Tertiary seas making it difficult to determine the exact outline of the San Joaquin "basin."

In the San Joaquin Valley, oil is found in almost every type of trap. Anticlinal structures with complications either by faulting or stratigraphic changes have accounted for the major volume of production. Examples of this type of accumulation are fields on the Coalinga-Kettleman Hills anticline, the Elk Hills-Coles Levee anticline, the Rio Bravo-Greely trend, the Wheeler Ridge-Tejon Ranch anticline and the Belridge anticline. Oil occurs in faulted homoclines on the east side of the valley at Round Mountain, Kern Front, Fruitvale, Mount Poso, and Mountain View. Sands open to outcrop but with low fluid level produce at East Coalinga. The Lakeview area of the Midway-Sunset field appears to be synclinal. Although sand is the reservoir rock for 95 percent or more of the fields, significant accumulations also occur in fractured shales at Elk Hills and Buena Vista Hills and in fractured schist basement at Edison.

Inclined water tables have been noted in the Coalinga Nose, North Dome of Kettleman Hills, Paloma, Coles Levee, Elk Hills, and other fields. Advocates of the hydrodynamic theory are opposed by those who consider such inclined water surfaces due to differences in permeability. In some cases water encroachment is opposed to direction of inclination.

In the future, stratigraphic and fault traps should account for a larger percentage of oil discovered in the San Joaquin Valley than in the past. Obscure structural highs revealed by subsurface geology, detailed geophysics, or other methods will undoubtedly contribute future discoveries. Recently, extensions and deeper drilling of known structures have accounted for substantial amounts of new oil and should continue to do so in the future.

## GEOLOGIC ENVIRONMENT OF CUYAMA VALLEY OIL FIELDS, CALIFORNIA

STANLEY A. CARLSON, MASON L. HILL, JAMES B. O'FLYNN AND IRVING T. SCHWADE

Richfield Oil Corporation, Los Angeles, California

Cuyama Valley, in the extreme southeastern part of the Salinas-Cuyama Tertiary basin of the southern Coast Ranges, contains two major oil fields—Russell Ranch and South Cuyama. They have produced respectively over 35 and 55 million barrels of 35° API gravity oil since mid-1948 and 1949. Production in the two fields is derived respectively from 290 and 480 feet of Vaqueros (lower Miocene) sands at depths ranging from 2800 to 4300 feet. The fault-closed reservoirs with respective areas of 1400 and 2500 acres are unitized and pressure maintained. In addition, there are three minor fields in Cuyama Valley. San Ardo, the only other major field, lies near the northern border of the basin and has been described previously.

The basin, which is 160 miles long and 28 miles wide, is bounded on the northeast and the southwest by the San Andreas and Nacimiento fault zones, respectively. It is underlain by granitic basement and contains up to 9500 feet of lower Miocene marine clastics. In the Cuyama-Carrizo portion of the Miocene basin a thick continental section grades southwestward into a very thick marine section composed principally of deltaic sand. This, in turn, changes rapidly to the thin marine organic shale and sand of the southwestern, oil-producing, shelf belt. This latter thickness and facies change is largely obscured by imbricate reverse faults of probable Quaternary age. Locally these faults have a prominent strike-slip component of displacement, which conceals at least one important, old and step lateral fault.

The original Salinas-Cuyama Miocene basin has been elongated many miles by cumulative movements on northwest-trending right

lateral-slip faults which now juxtapose formerly widely separated sedimentary facies. In Cuyama Valley, one of these is the buried Russell fault which traps most of the oil and another probable one, aided by reverse faulting, explains the close proximity of trough and shelf facies.

### THE DENVER BASIN—A STRATI-STRUCTURAL PROVINCE

CHARLES J. MCGINNIS
The California Company, Denver Colorado

The Denver basin covers some 58,000 square miles in portions of Colorado, Wyoming, South Dakota, Nebraska and Kansas, and is directly related to the series of intermontane basins developed in the Rocky Mountain mobile belt during the Laramide revolution. Sediments, although preponderantly Cretaceous, range in age from Cambrian to Recent, and attain a maximum thickness of 15,000 feet along the westerly asymmetric flank of the basin. While attention was focused on the area as early as 1862 with the discovery of oil in the Canon City, Colorado, area, the current heightened activity stems from the discovery of significant reserves of Cretaceous oil in the Nebraska portion of the basin during 1949. Two productive horizons have been defined: the sands of the Cretaceous Dakota Group accounting for the great bulk of the production, and the Permian Lyons sand currently productive in but one field. With the general absence of adequate structural closure, stratigraphic traps assume the primary role. The considerable random drilling encouraged by low well costs has largely masked the material contribution made by scientific methods, but an alliance of these two exploratory approaches has greatly accelerated the development of the basin. The cumulative production to July 1954 was 51,382,000 barrels. The estimated reserve of 87,000,0000 barrels at the end of 1953 has been at least doubled by drilling during 1954, attesting to the youthful stage of exploratory development in the basin.

### BRACKISH WATER AND ITS STRUCTURAL IMPLICATIONS IN THE GREAT CAROLINA RIDGE

H. E. LEGRAND
U. S. Geological Survey, Raleigh, North Carolina

The finding of surficial brackish water in Bladen County, North Carolina has led to a study of the Great Carolina Ridge, known heretofore merely as a wide, southeast-trending uplift of Cretaceous strata of the Atlantic Coastal Plain. The brackish water is unusual because of its surficial occurrence in the hinterland and because, as its chemical character proves, it represents artesian water rising to the ground surface along a fault, through breached clay beds and unconsolidated sands. The fault, trending northeastward, marks the west border of a broad, domed area of brackish ground water west of Wilmington. The area is elongated northeastward, indicating that northeast-trending structures form an impermeable barrier which has retarded the flushing of salty water from the artesian beds.

Microfaunal analysis of cuttings from four wells reaching basement, extending from Conway, South Carolina, through Wilmington to the vicinity of Jacksonville, North Carolina, indicates the absence of the Tuscaloosa formation, the basal outcropping formation of the Coastal Plain. This anomaly implies a Tuscaloosa land barrier along this line and a basin of undetermined proportions to the west. Distinctive littoral and outer neritic facies of the Peedee formation juxtaposed near the surficial brackish water suggests faulting rather than rapid deepening of sediments.

Available evidence, including published results of a magnetic survey, supports the existence of complex northeast-trending structures. Contrary to general opinion, the Carolina Ridge, containing an undrilled area of 8000 square miles, may have favorable structures deserving attention if oil prospecting is stimulated on the Atlantic Coast.

## HABITAT OF OIL IN THE DEPOSITION BASIN
(Parallel Session)

Presiding: VERNER E. JONES AND GAIL F. MOULTON

### PETROLEUM OCCURRENCE IN THE UINTA BASIN

LEWIS F. WELLS,
Sun Oil Company, Casper, Wyoming

The Uinta basin is characterized by a preponderance of petroleum occurring within its geographic borders in Utah and Colorado. The form, quantity and types of surface and subsurface occurrences make this sedimentary basin of prime interest to the oil industry of the Rocky Mountain province.

The surface deposits such as the bituminous sandstones of the Sunnyside area along the Book Cliffs contain saturated sandstones with a crude oil recovery of 94 percent for an estimated reserve of 1.5 billion barrels. Along Asphalt Ridge at the unconformable contact

of the Cretaceous and Tertiary are sandstones with a yield of 96 percent for an estimated recovery of 20,500,000 barrels per square mile and a total reserve of from 1 to 3 billion barrels of recoverable crude oil.

Solid and semi-fluid hydrocarbons such as the vein and fracture deposits of gilsonite, albertite, wurtzlite and ozocerite add to the potentiality of the basin. The kerogen shales of the Green River formation, particularly the Mahogany Marker unit, constitute one of the world's largest oil-shale deposits. This unit produces an average of 60–70 gallons of kerogen per short ton of shale and contains an estimated 400 billion barrels of reclaimable crude oil. New economic importance can be given the kerogen shales with the recent discovery of reclaiming them with a zinc catalyst. Great advancement can be expected in reclaiming the kerogen deposits of the Green River formation of the Uinta basin.

The subsurface of the Uinta basin also contributes to the petroleum reserve. Shows of oil and/or gas have been encountered in 95 percent of the wells drilled within the basin. Daily production is approximately 75,000 barrels, the greater part of which is from Rangely. Rangely field has produced in ten years approximately 140 million barrels of oil. Gas reserves for the Uinta basin are estimated at 575,000,000 MCF.

The general geologic features of the Uinta basin follow closely those of other Rocky Mountain areas having intermontane basins. The synclinal structure is moderately complex, with the axis trending east-west paralleling the anticlinal axis of the Uinta Mountains and is asymmetrical with the basin trough lying near the Uinta Mountain uplift. The structural form started in late Cretaceous and continued into late Tertiary time.

Paleozoic rocks 4300 feet thick represent all systems from Cambrian to Permian with the exception of Silurian. Mesozoic rocks 10,175 feet thick of Triassic, Jurassic and Cretaceous age are present with basin filling starting at the close of Cretaceous time. Lacustrine with nonlacustrine deposition continuted through the Tertiary to late Miocene time. These continental beds 11,000 feet thick contain a vast store of hydrocarbons and permeable sandstones which constitute large crude oil reserves. The oil and gas reserves together with various forms of hydrocarbons and surface accumulation of petroleum require only further economic development to increase the resources of our nation.

## HABITAT OF OIL IN THE SAN JUAN BASIN

SHERMAN A. WENGERD
University of New Mexico, Albuquerque, New Mexico

The San Juan basin is an ovate, frontal-intermontane, structural basin comprising about 20,000 square miles of area and 36,000 cubic miles of sedimentary rocks within the Dakota outcrop above the Precambrian basement. The basin is bounded by the San Juan uplift on the north, the Chama basin on the northeast, the Nacimiento uplift on the east, the Rio Grande depression on the southeast, the Mount Taylor volcanic complex and Acoma embayment on the south, and the Zuni uplift on the southwest, the Defiance uplift on the west, and the Four Corners structural platform on the northwest.

The area of the present San Juan basin was intermittently a southeastern sedimentational shelf and positive area related genetically to the Cordilleran geosyncline during Cambrian to early Pennsylvanian time; during Pennsylvanian time, the San Juan area was an unstable sedimentational shelf southeast of the Paradox geosyncline and bounded by the San Luis-Nacimiento coarse-clastic-producing highland on the north and east, and the Zuni-Defiance fine-clastic-producing positive areas on the south and west. During Permian, Triassic, and Jurassic time, the area was essentially one of continental clastic deposition with minor marine invasions from the southwest, west, and north. In late Cretaceous time, the area subsided gently as a highly oscillatory sedimentational shelf lying southwest of the Rocky Mountain geosyncline. Localized folding and faulting of diverse trends took place during the Laramide orogeny of latest Cretaceous to early Tertiary age. During and subsequent to Laramide time, the area was raised epeirogenically over one mile above sea level, as differential subsidence created a bowl-shaped depression into which were poured clastic continental fluviatile and volcanic sediments from the strongly rejuvenated ringing highlands.

From mid-Tertiary time to the present, successively older sedimentary rocks were exposed to erosion, ringing the youthful basin with breached anticlines, hogbacks, cuestas, and long arcuate monoclines flanking the tectonically accentuated marginal uplifts.

Oil in the San Juan basin is found in anticlinal, disconformal, and stratigraphic traps in the Ouray-Leadville-Hermosa carbonate rocks, and in anticlinal, terracic, disconformal, stratigraphic, fractural, and hydrodynamic traps in Entrada-Dakota-Mancos-Mesaverde-Farmington clastic rocks. With no proved exception, the oil in all strata of the San Juan basin is indigenous to the Paleozoic carbonate reservoirs, indigeneous to Mesozoic sandstones or derived from shales superjacent and subjacent to clastic reservoirs, or indigenous to fractured Mancos shale and siltstone.

The forces which caused the short-distance movements of oil to commercial accumulations

in Upper Cretaceous rocks are believed to have acted in approximately the following sequence:

(1) Compaction, (2) Laramide folding and minor faulting, (3) Tertiary differential subsidence to yield stratal dips approaching ten times the sedimentational slopes present in the late Cretaceous seas, (4) Tertiary hinge faulting accompanied by sharp uptilting of all Mesozoic rocks, (5) Major Tertiary normal and thrust faulting on the east side of the newly formed basin, (6) Meteoric water intake in the more porous upturned outcrops of Mesozoic rocks on all sides of the basin. Considerable overlap of orogenic and hydraulic events occurred throughout the Cretaceous to Tertiary history of the San Juan basin. This resulted in slightly tilted water-oil contacts in anticlinal traps, downdip wedge-edge accumulations of oil, fault accumulations, and localized basinward shift of oil accumulations within pre-subsidence structurally closed traps. In some cases there resulted a complete shift from these traps to nearby structurally open areas where oil is held in dynamic balance by fresh water moving in complex patterns in relation to the present outcrops.

The San Juan basin has all the characteristics necessary to qualify as a major oil-producing region, to wit: thickness of sedimentary rocks (16,000 feet), evidence of oil and gas (fields, shows, seeps), presence of unconformities (abundant), wedge-outs of porosity (abundant), geologic structure (well-developed), timing of events (little understood), hydrodynamics (well-developed).

The San Juan basin area is considered to be only 50 percent tested in post-Permian strata and 25 percent tested in pre-Permian strata despite the fact that virtually all the surface anticlines have had at least one test drilled to Dakota rocks. The explorer must recognize that all marine petroliferous strata in the San Juan basin were deposited prior to differential basining (habitat), and that all Laramide to Recent events had marked influence on the arrangement of oil into commercial pools (accumulation succeeded by shift). Careful subsurface analyses will result in discovery of new oil reserves in the San Juan basin.

## THE HABITAT OF OIL IN THE EASTERN GULF COAST

JULES BRAUNSTEIN

Shell Oil Company, New Orleans, Louisiana

The area discussed includes all of Mississippi, the coastal plain portions of Alabama and Georgia, and all of Florida. Oil and gas production in this province has been obtained from red-bed gravelly sandstones, deltaic sandstones, neritic sandstones, neritic limestones, dolomites, and chalk, ranging in age from Ordovician to middle Eocene. In order of importance, traps include (1) uplifts over deep-seated salt domes, (2) anticlinal uplifts, (3) closures along faults, (4) stratigraphic traps on low relief anticlinal noses, (5) fractured chalk, (6) a possible reef, and (7) closures associated with piercement salt domes. Through December 31, 1953, approximately 401 million barrels of oil had been produced in Mississippi, 6½ million barrels in Alabama, and 3½ million barrels in Florida.

## GEOLOGY AND HYDROCARBONS IN THE PO VALLEY BASIN

TIZIANO ROCCO AND DANTE JABOLI

AGIP Mineraria, Milano, Italy

The Po plain, from a geological point of view, may be divided into two regions: the Periapenninic trough in the south and the Pedealpine region in the north.

The Periapenninic trough is featured by continuous sedimentation from Oligocene to Quaternary and by a tremendous thickness of clays, marls and sandy sediments, mainly of a neritic facies. In this trough the Miocene and the Pliocene formations are folded with long and regular anticlines, while the Quaternary is subhorizontal.

In the Pedealpine region the basement is not so deep as in the Periapenninic trough and the Pliocene is transgressive on the middle Miocene or older formations. The pre-Pliocene formations are strongly deformed and eroded, while the Pliocene is only mildly folded, sometimes above buried hills.

Hydrocarbon shows, mostly gas, have been found in all the sedimentary series drilled from Quaternary to Oligocene. However, commercial pools have been found only on the tops of the anticlines from lower Quaternary (Correggio beds) to Tortonian (Cortemaggiore beds).

We presume that most of the hydrocarbons have accumulated on top of the anticlines by migration from the flanks rather than from vertical migration.

AGIP Mineraria has found eleven major gas fields (one with oil) and some others of little importance. Only eight of the eleven fields are actually producing, and these have an average daily rate of 10 million cubic meters of gas (350 million cubic feet). Additional daily production of 800,000 cubic meters (28 million cubic feet) of gas, with salt water, is obtained from "Upper Quaternary"

in the eastern Po plain by many small private companies.

## THE RELATIONSHIP OF OIL OCCURRENCE TO STRATIGRAPHY IN THE MIOCENE OF SOUTHERN TRINIDAD, B.W.I.

KENNETH W. BARR, STEPHEN T. WAITE, AND CEDRIC C. WILSON

Trinidad Leaseholds Limited, Pointe-a-Pierre, Trinidad, B.W.I., United British Oilfields of Trinidad, Limited, Point Fortin, Trinidad, B.W.I., and Trinidad Petroleum Development Company, Limited, Palo Seco, Trinidad, B.W.I.

Discussion is confined to the Miocene which includes the major oil producing formations of southern Trinidad, for although Oligocene and older production occur, the data available are as yet insufficient for a regional study of the pre-Miocene oil distribution. The Miocene stratigraphy has been broadly covered in previous literature; for the purpose of stratigraphic and paleogeographic studies the Miocene is here subdivided into three major sedimentation cycles corresponding approximately to the Morne l'Enfer, Forest and Cruse formations, respectively, from youngest to oldest.

During Miocene time the area of southern Trinidad formed a part of the Eastern Venezuelan geosyncline, and generally speaking the Miocene sedimentation reflects the progressive infilling of this subbasin, beginning with dominantly argillaceous deposits and passing through a series of clay-silt-sand cycles to dominant sand deposition of the final infilling phase. The main source of sediments, while generally from the south, appears to have varied from multiple sources from southeast and southwest in early Miocene to dominantly from southeast to east in late Miocene times. The dominant sand deposition appears first in the southeast, spreading right across the entire area by late Miocene times as represented by the very uniform deposits of the Morne l'Enfer formation.

The pre-Miocene structural pattern was closely related to present-day features and influenced local depositional trends, but in general the Miocene formations thin northward and sands tend to wedge out in this direction also. The complex Central Range uplift seems to have formed a barrier to the north throughout most of the Miocene but in upper Miocene times it appears that this barrier became less effective and communication was finally established between the northern and southern sub-basins. Over much of the area in early to middle Miocene times sedimentary conditions were very variable with submarine slumping, channeling, and turbidity current action playing an important part. As a result, rapid lateral variations and marked lenticularity are frequent. The variable environment is reflected in the foraminiferal microfaunas which show strong facies influence, rendering correlation often a matter of great difficulty even over relatively short distances. The oil-bearing formations are thus made up of a multiple series of lenticular sand reservoirs of very variable extent.

Post-Miocene folding of the Andean revolution accentuated earlier structures and superimposed new fold trends. The fold pattern shows a distinct southward asymmetry directed towards the Guayana foreland. The Miocene basin of southern Trinidad was steeply folded along its northern rim while along the southern side broader structures tend to prevail. Later regional adjustment movements expressed in the southeastward trending Los Bajos tear fault resulted in the present configuration.

The factors determining oil occurrence are not fully understood; the pattern of oil occurrence as revealed by the existing oil field shows the interplay of stratigraphic and structural features. The sharply folded structures along the northern rim of the basin are generally oil-bearing as combination structure-stratigraphic trap fields, whereas the less distributed southern flank of the basin is the locus of a stratigraphic trap field the extent of which has yet to be fully explored.

On the basis of oil composition there is little doubt that the bulk of the Miocene oils are indigenous, and while there is evidence for redistribution and modification of oil impregnation by faults, vertical migration and secondary impregnation by many of the faults and fractures appear generally to have been of minor importance. However, exception to this statement may be made in the case of the Los Bajos fault, as the occurrence of the major Miocene producing field adjacent to, and in several cases abutting, the fault indicates that it has played a significant role in determining oil occurrence. In some cases it appears to have acted as a simple fault trap; in others redistribution of oil along or through the fault plane has resulted in anomalous oil occurrences.

The general picture which emerges from this study is that the bulk of the Miocene oil is indigenous to the formations in which it occurs and that oil distribution appears to be controlled mainly by a combination of stratigraphic and structural factors; that is, by lenticularity of the sands and by the occurrence of fold structures aroung the rims of the basin.

## NOTES ON THE TECTONICS OF SOUTHERN MEXICO*

ZOLTAN DE CSERNA
Instituto Nacional Para la Investigacion de Recursos Minerales, Departmento Geologico, Mexico 4, D. F.

Compilation of the new geologic map of Mexico resulted in the accumulation of published and unpublished data from Mexican Government agencies which enabled the preparation of a tectonic map of southern Mexico, south of latitude 20° N. The major structures are discussed in chronological order as to the age of their principal rocks and the deformations they record.

The Isthmian Province contains Precambrian gneisses and schists which are overlain by lower Paleozoic metasediments. Middle Paleozoic batholithic intrusions and late Paleozoic basic intrusives complete the pre-Miocene record. Metasediments of possibly early Mesozoic age overlie Paleozoic metamorphics, and batholithic intrusions of possibly middle Mesozoic age overlain by late Mesozoic sediments make up the principal rock sequence in the Sierra Madre del Sur Province. The Sierra Madre Oriental Province consists of late Mesozoic sediments which lie over a basement formed by Paleozoic metamorphics. Tertiary and Quaternary sediments overlie Mesozoic and possibly Paleozoic sediments in the Gulf Coastal Plain-Yucatan Province.

Rocks in the Isthmian Province record orogenies during the Precambrian but the trends are not yet established. In this province the northeast-southwest trend is a result of late Paleozoic deformation. The general strike direction of possibly middle Mesozoic age in the Sierra Madre del Sur Province is north-south. Structures in the Sierra Madre Oriental Province trend in a N 45°W direction, hence are related to the early Tertiary deformation. Late Cenozoic volcanism resulted in a distribution of volcanoes in an east-west belt. This belt might reflect a zone of oblique shear of the late Cenozoic orogeny along the Pacific margin of North America. A zone of block faults along the Pacific Coast of southern Mexico is believed to have resulted also from this late Cenozoic orogeny.

## MISSISSIPPIAN STRATIGRAPHY AND SEDIMENTATION IN WYOMING AND SOUTHERN MONTANA

JOHN M. ANDRICHUK
Alex W. McCoy Associates, Calgary, Alberta, Canada

Pre-Pennsylvanian erosion determined the present limits of Mississippian occurrence on the southeast. The zero line passes through southeastern Wyoming, northwestern Nebraska and adjoining South Dakota. The Mississippian section thickens west to the Idaho geosynclinal trend and north to the central Montana trough and Williston basin.

Lithologic sequences developed in the Madison-Charles group of central Montana continue south to their truncated edges in Wyoming and western South Dakota. Three cartographic sequences are recognized: a lower unit correlative approximately with the Lodgepole formation; a middle unit including the Mission Canyon and basal evaporite zone of the Charles formation; and an upper unit consisting of Charles strata above the basal evaporites.

Evaporite cycles, characterized by lithologic variation from fossiliferous-fragmental or oölitic and normal marine limestones (or dolomitized equivalents) to restricted-type carbonates and anhydrites, are developed within the upper and middle units. South from central Montana, the normal carbonates are generally dolomitized. Moreover, the evaporitic lithologies of each sequence or cycle indicate a lesser degree of restriction during sedimentation in the southern areas.

Productive and potentially productive oil zones are present within the normal carbonates of each cycle. The associated evaporitic rocks indicate favorable situations for the preservation and entrapment of hydrocarbons in the subjacent carbonate reservoirs. Lateral facies variations from porous secondary dolomites to relatively dense limestones may provide the trapping component in some areas.

## SOUTH BLANCO TOCITO SAND FIELD

GAIL F. MOULTON
Rockefeller Bros., Inc., New York, New York

The South Blanco Tocito Sand oil field, Rio Arriba County, New Mexico, at present is the most important source of oil in northwestern New Mexico. The discovery well was completed in July 1951 at a depth of 6700 feet. To the end of 1954, production has exceeded 1,250,000 barrels, of which 416,000 barrels were produced during 1954 from 14 wells.

Oil and gas accumulation are controlled by the local development of the Tocito Sand, an approximate equivalent of the Frontier of Wyoming. The producing area of about 3000 acres is one to one-and-one-half miles wide and elongated in an east-west direction. The top of the producing zone dips about 50 feet per mile in a northeasterly direction. A gas cap occurs in the highest portion of the sand

* Publication authorized by Director of Instituto de Geología de la Universidad Nacional Autonoma de México.

body. No other effect of structure on accumulation has been determined.

An opportunity for the application of reservoir performance data to the solution of exploration and exploitation problems was created by the control, under one ownership, of the leases in the area of initial development. Reservoir pressure behavior during the early production period suggested a substantial volume of connected productive sand, After completion of the third oil well, additional pressure measurements served to indicate the directions from which reservoir energy was coming into the producing area. Thereafter, development well locations were chosen in the indicated direction of the energy sources. Additionally, as exploitation continued, projections of isopach data for the unexplored area were combined with energy studies for this purpose. These techniques resulted in avoidance of dry holes, few marginal wells and for much of the field a spacing pattern of 160 acres per well with demonstrated continuity of the reservoir between wells.

Basically similar fields are being discovered and developed in eastern Colorado, central Wyoming and other parts of the Rocky Mountain region. It is anticipated that the methods used in South Blanco might contribute to the economic success of their exploration and exploitation.

# ABSTRACTS OF PAPERS
# 1954 ANNUAL MEETING, PACIFIC COAST SECTION
# SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

The 1954 Annual Meeting of the Pacific Coast Section of the Society of Economic Paleontologists and Mineralogists was held in Los Angeles, California, on November 11 and 12.

Pacific Coast Section officers for 1954–55 are as follows:

*President:* John W. Ruth, Los Angeles, California

*Secretary-Treasurer:* Wayne Elliott, Long Beach, California

## ANNUAL DINNER AND EVENING SESSION

### November 11, 1954

Presiding: JOHN W. RUTH AND WAYNE E. ELLIOTT

### NEW METHODS OF IDENTIFYING SEDIMENTARY ENVIRONMENTS*

FRANCIS P. SHEPARD

Scripps Institution of Oceanography, University of California, La Jolla, California

The study of sediments in the northern Gulf of Mexico, a project now in its fourth year, has been a cooperative undertaking involving to varying extents about half of the faculty at Scripps Institution in addition to several scientists at other universities and a full time staff of fourteen at Scripps. The purpose has been to develop methods whereby the depositional environment of ancient sedimentary formations can be identified from the knowledge of present day sediments. The field work has been concentrated in two major areas, one along the central Texas coast and the other along the eastern side of the active Mississippi Delta. A third area investigated on a smaller scale has been Florida Bay and the Keys with their offlying reefs. The study of sediments from all of these areas has yielded criteria which make it possible to recognize the various environments in which the different materials have been deposited. This has been possible through cooperative studies involving many aspects of sedimentology, biology, and chemistry. Among the methods which have been developed or expanded are the following:

1. Estimating the volume of and counting the important constituents in sievings of the Wentworth grade sizes; results are used to characterize environments.
2. Statistical analysis of the assemblages of Foraminifera, Ostrocods, and macroorganisms relating them to geographic and hydrographic environments.
3. Relating clay mineral abundance to distance from river mouths and to distance from shore on the continental shelf.
4. Relating chemical constituents, such as $CaCO_3$, to distance from the rivers introducing the sediment.
5. Developing the relationship of grain roundness to environments, particularly as a means of distinguishing beach and dune sands.

* Work based largely on investigations carried out under American Petroleum Institute Project 51.

6. Plotting in three-dimensional diagrams the interrelations of median diameter and measures of sorting and skewness, so that these factors could be related to environments.
7. Relating of sand-silt-clay percentages to depositional environments.
8. Computing of grain orientation with reference to depositional environments.

Using these methods it has proven possible to identify with considerable accuracy the environments of various test samples of modern sediments. Also samples from borings down to about 80 feet in the Recent deposits along the Texas coast have been examined and the methods appear to be almost as applicable to these older sediments as they are to those at the surface. There seems to be no reason why similar and improved methods should not apply to most other types of sedimentary environments, making it possible to get out of the horse and buggy era in which the nature of basins of deposition are determined by using old dogmas based largely on philosophical concepts rather than on a knowledge of present day sediments and on sedimentary processes in the present seas.

## GENERAL SESSION

### November 12, 1954

Presiding: HANS E. THALMANN, AND U. S. ARMSTRONG

### RECENT LITTORAL FORAMINIFERA FROM THE COAST OF SOUTHERN CALIFORNIA

EMIL R. ZALESNY
University of Southern California, Los Angeles, California

Foraminifera were collected from tide pools, marine lagoons, and the open coast line from Laguna Beach to the Malibu area. They are much more abundant in the quiet tide pools and lagoons as contrasted to the turbulent surf zone.

Certain species were present in all environments tested, while other species were restricted to only one type of environment. *Elphidium translucens* and *Streblus tepidus* were only found in lagoons, while *Rotorbinella versiformis* and *Cibicides fletcheri* seemed to prefer tide pools.

Foraminiferal assemblages of similar environments were quite uniform all along the ninety miles of the coast line examined.

### ECOLOGIC REQUIREMENTS AND DEPOSITIONAL ENVIRONMENTS OF PLEISTOCENE MOLLUSCAN FAUNAS FROM SOUTHERN AND BAJA, CALIFORNIA

JAMES W. VALENTINE
University of California, Los Angeles, California

A series of molluscan faunas has been collected from marine Pleistocene terrace deposits along the northwest coast of Baja, California and in the southwestern corner of the United States. From the position of each fossil locality relative to the configuration of the shore line at thet ime the faunas were deposited, it is possible to refer the ecologic elements of each assemblage to habitats which existed along the Pleistocene coast, and to infer an environment of deposition for each locality.

Ecologic analyses of the faunas in terms of the Recent distribution and habitat of the species show certain marked differences between the specific constitution of Pleistocene and Recent assemblages. At nearly every locality are found mixtures of forms that require temperatures both warmer and cooler than are normal at present in nearby ocean waters. Most cool water fossils are offshore or exposed coast forms, while most warm water fossils are embayment or protected coast forms. It is suggested that, at the time these faunas lived, near-shore waters were significantly warmer than at present, and that the cool waters of local upwellings had lower temperatures than similar upwellings today along northern Baja California. Such changes in water temperatures are probably related to factors causing, or to effects of, Pleistocene glaciation.

### RECENT DEVELOPMENTS IN ANTHROPOLOGY

H. R. GALE
Pasadena City College, Pasadena, California

Many new and surprising finds and the reinterpretation of older ones have greatly changed our understanding of the early history of men and its significance. A few skeletal remains and indirect evidence from cultures and other sources indicate that the progressive *Homo sapiens* type of man is much older than has in the past been generally recognized. From this largely European main line of evolutionary development, the degenerate, mainly Asiatic *Pithecanthropus* branch split off in lower Pleistocene time, with its unprogressive cultures. The still more degenerate ape-man or man-ape group represented in Africa by

*Australopithecus* and its relatives in southeast Asia by similar grotesque forms may be an extreme derivative from the *Pithecanthropus* branch, with which it is closely associated in time and place in both areas, or it may possibly be an earlier branch. The upper Pleistocene Neanderthal or *Protanthropus* branch is now shown to be an unusually late degenerate split from the main line. Since that time, human evolution has been psychological, rather than physical.

## A COMPARISON OF MIOCENE AND RECENT SILICOFLAGELLATES

ROBERT H. MCGLASSON
University of Southern California, Los Angeles, California

Silicoflagellates are microscopic protozoans with internal siliceous skeletons. They are especially found in diatomaceous earth, and thereby their presence has been noted by the students of diatoms.

Their study has been extremely limited. G. D. Hanna is the only American to have analyzed them to any degree. He has pointed out their value to the stratigrapher.

Classification of the Silicoflagellates is based upon their characteristic shapes and ornamental structures because their protoplasmic body is very imperfectly preserved even in Recent forms.

The Silicoflagellates range in geologic time from the Cretaceous to the Recent. The older forms are relatively simple and consist mainly of a triradiate skeleton.

A study was made to compare the type and relative number of Silicoflagellates found in the Valmonte diatomite (Miocene) of the Palos Verdes Hills to those found in the siliceous sediments now being deposited in the Gulf of California. Recent plankton of the Southern California waters were also examined.

## THE BIOLOGIST'S POST-WAR CONTRIBUTIONS TO THE STUDY OF THE FORAMINIFERA

ZACH M. ARNOLD
University of California, Berkeley, California

The following contributions from the laboratories of LeCalvez (France), Grell (Germany) and Arnold (America) are among those discussed:

1. A textbook account of foraminiferal biology in "Traite de Zoologie."
2. The discovery that the reduced (haploid) chromosomal complement is not confined to sex cells of *Patellina corrugata* but characterizes an entire generation of the two-generation life cycle.
3. An extension of this observation to *Rotaliella* and *Allogromia*.
4. The observation that a single individual of *Allogromia laticollaris* may produce gametes which fuse to form a new generation without the intervention of a second parent—a type of uniparental "sexual" reproduction known as autogamy.
5. Additional evidence of basic cytological dimorphism underlying and correlated with test dimorphism.
6. A suggestion of biochemical differences between the two sexes in *Discorbis mediterranensis*.
7. The demonstration of the conspecificity of *Discorinopsis aguayoi* and *D. vadescens* through the study of variation in populations from laboratory cultures.
8. The suggestion, derived from a study of variation in laboratory populations of *Allorgomia laticollaris*, that a given plan of growth and/or chamber shape may arise in more than one way or from more than one ancestral type.
9. A demonstration of the basic organizational plasticity of one species (*Allogromia laticollaris*) within the stock complex from which all foraminifera are believed to have arisen.

## FORAMINIFERA AND FISH SCALES FROM THE MODELO FORMATION

RICHARD L. PIERCE
Richfield Oil Corporation

The frequency distribution of ninety-five species of Mohnian Foraminifera and twelve families of Mohnian fish are covered in this paper. The area under discussion is located in Benedict Canyon, eastern Santa Monica Mountains (parts of sections 27 and 34 of Township 1 North, Range 15 West, Van Nuys Quadrangle, Los Angeles County, California). A stratigraphic thickness of some 2240 feet, consisting of northward dipping siliceous shales, massive sandstones, cherty shales and punky diatomaceous shales (older to younger rocks, respectively), are exposed at this locality. One hundred and thirty-five samples were examined along the bedding planes for fish scales, fish skeletons and Foraminifera; and later washed for the frequency distribution study of Mohnian Foraminifera. Some of the striking results are: Lower and Upper Mohnian sediments can be distinguished by the author, locally, by the use of either Foraminifera or fish scales; the Modelo formation at this locality was probably deposited in a bathyal zone; and the fish remains serving to better evaluate the ecology of the fossil Foraminifera in the Teritiary rocks of California.

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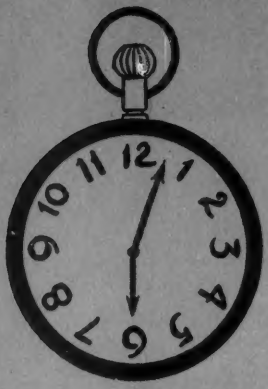

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